VI. *Contributions to the Physiology and Pathology of the Mammalian Heart.*

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SECTION I.—INTRODUCTORY.

The observations upon which the following communication is based were made upon the Mammalian heart under conditions as nearly approaching the normal as we were able to make compatible with the employment of accurate recording methods. Our object throughout has been to study the mechanism of the Mammalian heart *in situ* by methods of research which would give to the subject a degree of exactness as closely as possible approximating to that of the work of Kronecker, Coats, Gaskell, Heidenhain, &c., on the excised hearts of cold-blooded animals, and of N. Martin and his school on the excised Mammalian heart.

It need hardly be said that the mode of action of the heart of warm-blooded Mammals is a much more difficult subject of study than that of the heart of a Frog or Tortoise. The hearts of these latter animals are simpler in structure, to begin with, than those of a Rabbit, Cat, or Dog, and if the subject be further simplified by excising the organ and keeping thereby under control the nerve impulses which reach it, as well as the pressure and composition of the blood which enters and leaves its cavities (supposing the heart to be supplied with blood at all), some of the difficulties are greatly reduced. In the excised surviving heart of cold-blooded animals we have a piece of machinery whose action and attributes can be studied with a degree of accuracy and ease which corresponds with its comparative simplicity.

The Mammalian heart, on the other hand, is highly differentiated, and if it be sought to study its action while it continues to perform its function in the economy, with its nerves intact and liable to be called into activity by reflex excitation, with the blood-pressures in the systemic veins, the pulmonary artery, the pulmonary veins and the aorta subject to wide variations, with the composition and volume of blood reaching the heart in a given time liable to considerable changes, it might well seem, at first sight, hopeless to obtain data at all comparable in accuracy with those which have been obtained regarding the excised heart of the Frog or Tortoise.

It is, of course, easy enough to make some kinds of observations on the intact

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Mammalian heart, *e.g.*, on the influences which affect its rate of beat, the relation in time between the auricular and ventricular contractions and like matters, where simple inspection, or the employment of very simple recording apparatus, give the required data. When, however, it is sought to look more closely into the subject, to study, for example, the manner in which the different parts of the heart are affected by the nerves which enter and leave the organ; in what way the system as a whole is benefited by the existence of these nerves; in what way the heart adapts its force and frequence to the varying requirements of the economy, and how it is prevented from wasting its energy needlessly; how the heart is affected by such changes in the conditions as it is exposed to within physiological limits, or the still more interesting subject of the physiology of the heart in disease of the organ; when it is sought to study such parts of the physiology of the heart, the difficulties met with are considerable.

Owing to the complicated nature of the problems to be solved, we found it necessary to make a very large number (hundreds) of experiments, and to extend the duration of our studies on the subject far beyond what we anticipated on first taking the matter in hand.

Our observations were commenced some ten years ago in the late Professor COHNHEIM'S laboratory at Leipsic, and have been continued, with frequent intervals, till the present time, the work being done partly at the Brown Institution, but mainly during the last four years, when we have been working together, in our own laboratory here.

We have thought it best to defer publishing our observations until the present time, for the reason that, at each successive stage, further control experiments appeared necessary, and because we wished to avoid setting forth crude and insufficiently considered results. If we now make our results public, it is not because we feel that we have by any means exhausted the subject, but because we have, in our opinion, sufficiently controlled our observations upon some points to make it possible for us to publish them without grave misgivings.

One consequence of deferring the publication of our work has been that some of our less important results have been forestalled by other workers; this, as we knew, was unavoidable, but on the whole we thought it wiser to be in no hurry to describe our observations, and to wait until we could feel thoroughly at home with our subject.

The difficulties in our way could, some of them at all events, have been overcome had we followed the example of N. MARTIN and his pupils and worked with the excised Mammalian heart; we wished, however, to avoid, as far as possible, placing the organ under conditions which differ so widely from the normal, and preferred to work with it unsevered from the central nervous system and from the rest of the circulation, in the belief that our results would thereby be more directly applicable to what obtains in the normal condition. It appeared to us that the relationship of the heart to the rest of the economy is of special interest and importance, and it did not

seem possible to us to obtain other than imperfect information upon this subject by studying the excised surviving heart either of Mammals or of cold-blooded animals.

The difficulties met with in an enquiry into the attributes of the living unexcised Mammalian heart centre, as might be expected, round the methods of research which are employed. We, of course, used the graphic method, but soon learnt that no single piece of recording apparatus can give information upon all the various factors which together make up the cardiac mechanism. We have repeatedly found it necessary to get new instruments made which were fitted to give information on individual points which required to be investigated or controlled. Generally speaking, these methods have included the intracardiac pressure in the various cavities of the organ, the antero-posterior diameter of the ventricles, the changes in volume of the whole heart, the contractions of the heart wall at different parts and of the "musculi papillares," the arterial and venous pressures, and the pulse-wave. A small portion of our work, bearing especially upon the pathology of the heart, has already been published,* as has also another small portion bearing upon the part played by the heart in influencing the form of the pulse-wave.† In the following pages we have sought to avoid, as far as possible, the repetition of anything which has appeared in the papers here referred to. [We have made a very large number of observations on the Pharmacology of the Mammalian heart, the results of which, in order to avoid overloading the present paper, will be published on some future occasion.]

According to our experience it is necessary to proceed very circumspectly in the interpretation of graphic records from the Mammalian heart, and, so far as we know, the best, and indeed the only way, to avoid falling into error is to take care to control the observations made with one method by means of experiments in which some other method has been used.

SECTION II.—METHODS.

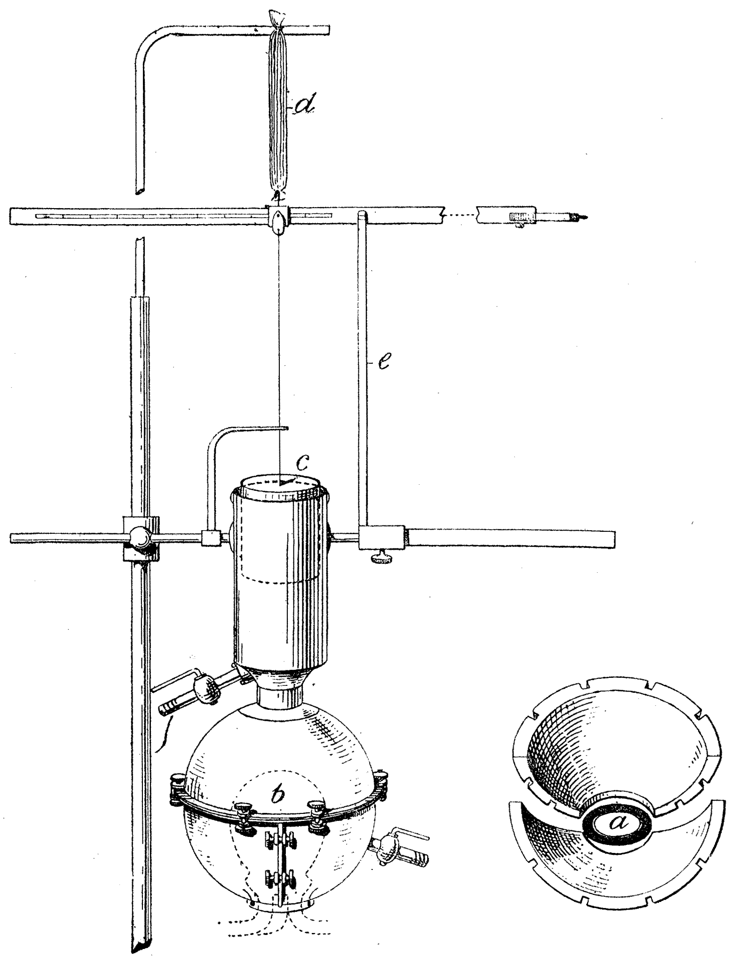
We have constantly, in the course of our work, been reminded that the graphic methods which may be used for studying the heart's action may very easily lead to erroneous conclusions unless it be known what are the sources of error inherent in any particular method employed, and also, unless it be kept clearly in mind what kind of facts the employment of any given method is capable of supplying, and what kind of facts it is unfitted to elucidate. In the observations which are recorded in the following pages, we have made use mainly of two forms of cardiograph, one of them, the *cardiometer*, being arranged to record the changes in volume which the heart undergoes; the other, the *myocardiograph*, giving graphic records of the contractions of any part or parts of the wall of the heart in the same way as an ordinary myograph records the contractions of a voluntary muscle.

* ROY and ADAMI, "On Overstrain of the Heart," 'British Medical Journal,' December 15th, 1888.

† ROY and ADAMI, "Heart-beat and Pulse-wave," 'Practitioner,' February to July, 1890.

It may be as well, however, to repeat that whenever, in the course of our work, we found it desirable to obtain information regarding other characteristics of the heart's action than can be learned by the employment of these instruments, we made use of a number of other apparatus, but as we base what we have to say below almost entirely upon the information obtained by the cardiometer and myocardiograph, it is not necessary for us to describe other methods here.

Fig. 1.



The Cardiometer. [One quarter natural size. Described in text.]*

A. The Cardiometer (fig. 1).†

The principle of this instrument can be gathered from an examination of fig. 1. When in use, the whole of the heart—in our experiments the Dog's heart—is enclosed in a rigid-walled box, the pressure within which can be varied at will; it is

* The bracketed additions to the explanations of the figures inserted July 20, 1892.

† All our instruments were made for us by the Cambridge Scientific Instrument Co., St. Tibb's Row, Cambridge.

connected with an arrangement for recording graphically the changes in volume of the heart. In other words, it is a cardiac plethysmograph, or oncograph.

It has been sought by FRANÇOIS-FRANCK,* JOHANSSON and TIGERSTEDT,† and others to use the pericardial sac as a cardiometer, but the objections to its employment are considerable on account of the flexibility of its walls, which necessitates that the pressure of the fluid which is introduced should be higher than the pressure of the atmosphere, whereby the heart is at once placed under abnormal conditions. The distensibility, also, of the parietal pericardium necessarily interferes greatly with the accuracy of the results obtained by this method. If it be desired to gain records of the changes in volume of the heart with any degree of accuracy, it is essential that the organ should be enclosed in a rigid-walled box, and the only real difficulty to be overcome in the employment of such a method is to make the instrument of a kind which, while it encloses the whole heart, does not interfere with the flow of blood to and from it through the large vessels at its root, and which does not allow any of the fluid surrounding the heart to escape by the sides of these vessels.

The method which we made use of to attain these objects was to attach the parietal pericardium (close to its reflexion on to the great vessels) to the edge of the aperture in the box through which the vessels passed. In order to fit the instrument to the hearts of different sized dogs, the lower half of the spherical box, *b*, was made in duplicate, the aperture in one being fitted for the hearts of large dogs and in the other for those of small ones. As the vessels at the root of the heart form together a mass whose circumference is much less than that of the organ itself, the lower portion of our box was constructed in two segments, the junction between which could easily be made air-tight by means of screw clamps, a stiff mixture of resin and lard being used as a cement; this arrangement allowed the aperture to be small, without its being necessary to push the heart through it.

Having opened freely the pericardial sac, the parietal pericardium is fixed to the edge of the aperture in the heart-box by applying round the root of the heart an oval metal ring composed of two separate halves. This ring is placed inside the pericardial sac close to the junction of its parietal and visceral layers. Round this ring, which is grooved to receive it, is a ring of india-rubber, *a*, circular in cross-section like an ordinary umbrella ring. Between this and the edge of the aperture of the box comes the parietal pericardium, the edge of the aperture being grooved to receive the rubber ring, and of such a size that the india-rubber is compressed, and the pericardial membrane with it, sufficiently firmly to prevent any escape of the fluid with which the box is to be filled.

The rest of the instrument is shown sufficiently clearly by the figure. Above, there is a light, hollow, vulcanite piston, *c*, which is attached to a long recording lever; this can be pulled upwards by a long india-rubber band, *d*, so as to reduce the

* FRANÇOIS-FRANCK, 'Trav. du Lab. de MAREY,' 1877, p. 197.

† JOHANSSON and TIGERSTEDT, 'Skandinavisches Archiv für Physiologie,' vol. 2, 1891, p. 409.

pressure round the heart below that of the atmosphere, entrance of air by the side of the piston being prevented by a thin flexible animal membrane, in a manner similar to that employed by one of us in an instrument for recording the changes in volume of the Frog's heart.*

In making the actual experiment, the dog having been fully anæsthetised, a dose of curare which is just sufficient to paralyse the nerve-endings of the voluntary muscles is injected into one of the veins, the respiration being carried on artificially, and the heart is exposed by making a large opening in the thorax. The pericardium is opened and the heart is introduced into the cardiometer, which is then filled up with warm olive oil, the pressure within the box being reduced to some 5–6 mm. Hg below that of the atmosphere by means of the india-rubber spring, *d*. Once satisfactorily started, the experiment can be continued all day if desired.

The instrument gives a graphic representation of the changes in volume which the heart undergoes at each contraction and expansion. It enables us to measure the volume of blood which enters and leaves the heart at each diastole and systole, the extent of each upstroke of the lever point corresponding to what STOLNIKOW† has named the "contraction-volume"—or rather to twice his contraction-volume, since he measured the volume expelled by the left heart only—while the cardiometer measures what is expelled by both ventricles. The method enables us to measure also the amount of blood passing through the heart in a given time—what STOLNIKOW has termed the "Strom-stärke," but which we prefer to call the "output" of the heart. When, for example, we say that the output of the heart was, in any given case, 100 c.c. in 5 secs., we mean that that amount was expelled by the right and left ventricles together, the output of each of the ventricles being, of course, only 50 c.c. in 5 secs., so that the "output" of the heart in our sense is twice STOLNIKOW'S "Strom-stärke."

The output is measured on cardiometer curves by adding together the heights of all the upstrokes made by the lever point during a given number of seconds or minutes.

It might be thought that the inflow of blood into the auricles during the time of the ventricular contractions would be subject to such variations as to vitiate the results obtained by the cardiometer, and we ourselves were not inclined, *à priori*, to look upon the results obtained by its help as being by any means free from this source of error. Further acquaintance with the method, however, and such control experiments as we have made, lead us to believe that any error due to variations in the amount of blood entering the auricles during the periods of ventricular systole must be so slight that it may be neglected, unless it be a question, not of studying the changes in the contraction-volume under different conditions, but of measuring exactly the volume of

* ROY, "The Influences which Modify the Work of the Heart," 'Journal of Physiology,' vol. 2.

† STOLNIKOW, "Die Aichung des Blutstromes in der Aorta des Hundes," DU BOIS REYMOND'S 'Archiv,' 1886, p. 1.

blood expelled at each contraction. As, however, the "contraction-volume" of the heart is subject to very great variations, it seemed to us to be of comparatively slight importance to know its exact measurement under any one set of conditions, and we have not sought to find how far the cardiometer gives this measurement. We have every reason for believing that the apparatus gives trustworthy information regarding the changes in the contraction-volume. We must add that the results obtained by the aid of this instrument can be controlled by the use of the myocardiograph. For example, it might be thought that any given change in the volume of the heart might be due to a change in the volume of one of the ventricles, the other being unaffected. This source of error can be controlled by repeating the experiment with the myocardiograph, recording simultaneously the contractions and expansions of the two ventricles.

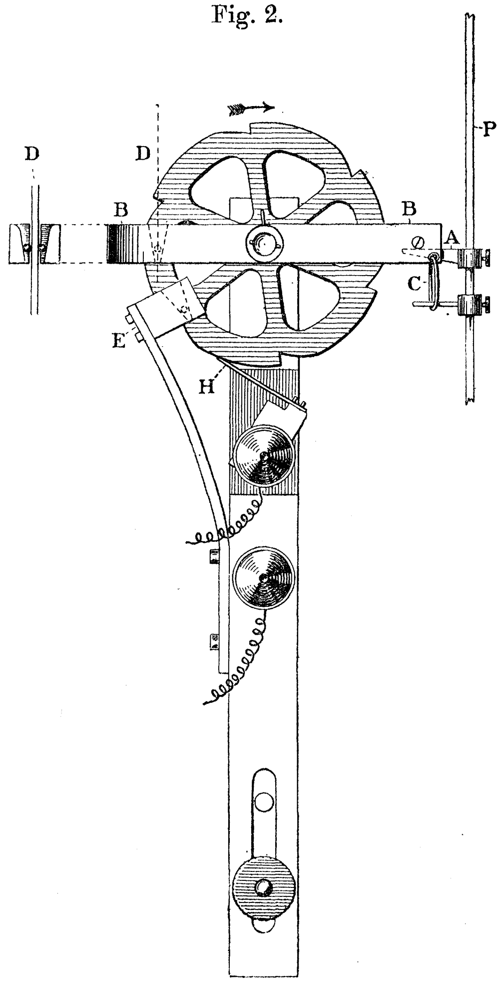
By the same means, also, we can learn whether any change in volume is due to the auricles and not to the ventricles. And it must be understood that when, in the following pages, we refer to data obtained by the cardiometer, we have convinced ourselves, in each case by control experiments, that the curves will bear the interpretation which we give to them.

The Automatic Counter (fig. 2).

In measuring out our cardiometer tracings, in order to find whether any change in the character of the curves was accompanied by a change in the output, we found that the time spent in determining the length of each upstroke, and adding the values together, was considerable, and that, moreover, it was difficult to eliminate errors due to uncertainty as to the *exact* number of beats, and fractions of beats, which occurred during a given number of seconds, although this could in all cases be found by taking sufficient trouble over the measurements. As, however, we grudged the time devoted to this necessary but laborious work, we found it desirable to make use of some method which would measure out for us, and record automatically on the tracing, the exact output of the heart. The illustration, fig. 2, represents an instrument which we found extremely accurate and convenient for this purpose. It consists of a light brass wheel, which is turned in one direction, shown by the arrow, by the downward movements of the cardiometer piston. To the piston-rod (P) of the cardiometer is fixed a light horizontal metal pin (A), on which, by a knife-edge, there rests one end of the horizontal lever (B), which is slung loosely on the same axis as the rotating wheel, the knife edge of this lever being kept in contact with the metal pin by a spring of india-rubber thread (C). At the other extremity of the lever are cut two semi-conical slots (D), one on each side of the wheel, in which are placed a couple of No. 5 "small shot," so that, when this end of the lever moves upwards, the lead pellets become jammed against the sides of the rim sf the wheel, which, therefore, moves with the lever. When, on the other hand, with the rise of the piston-

rod of the cardiometer which accompanies diastole, the left-hand end of the lever (B) has a downward motion, the wheel cannot turn backwards because the shot are no longer jammed between the lever and latter, and because the latter is prevented from turning backwards by the jamming of another couple of shot lying in semi-conical slots in a support (E) attached to the stem of the instrument. By means of these friction-catches the wheel is made to turn, with each contraction of the heart, to an extent which corresponds exactly with the volume of blood expelled by the organ.

Fig. 2.



The Automatic Counter. [Two-thirds natural size. Described in text.]

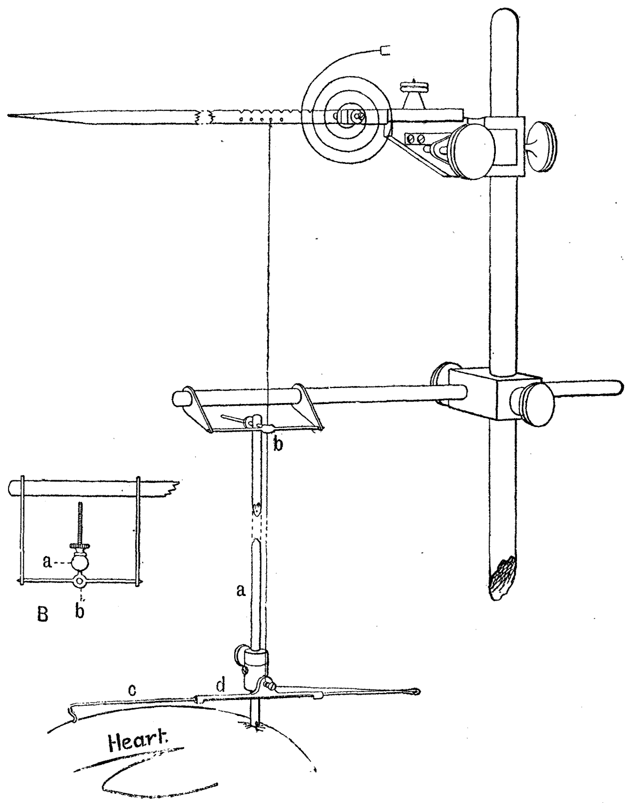
Having found (as can easily be done) the volume which corresponds to unit descent of the cardiometer piston, we had the wheel of the counter made so that one revolution corresponds to the output by the heart of 600 c.cm. of blood, and on the periphery of the wheel we had cut six equidistant notches. Pressing lightly against the edge of the wheel is a spring electric contact (H), which is interrupted by each notch upon the wheel, and, as each opening and closing of the electric circuit is

recorded on the drum by an electro-magnet, simultaneously with the cardiometer tracing and of the seconds time-marker, we have a graphic record of the time which has been required to expel each 100 c.cm. of blood. This instrument saved a great deal of the time and labour which would otherwise have been spent in measuring out our curves.

THE MYOCARDIOGRAPH (fig. 3).

We have given this name to the instrument we are about to describe, because it supplies us directly with graphic records of the contractions of the muscular wall of the heart. It consists in principle of an arrangement by which the variations in the distance from one another, of any two points upon the heart wall, can be magnified and traced upon the surface of a revolving cylinder without restraining either the contractions of the heart wall or the movements of the heart. One important advantage of the instrument consists in the fact that, by its means, it is possible to obtain simultaneous graphic records of the contractions and expansions of the wall of one of the

Fig. 3.



The Myocardiograph. [Half natural size. Described in text.]

auricles and of that of the corresponding ventricle, or, if it be desired, simultaneous tracings from the right and left ventricles, or again, of the ventricle and the *musculi*

papillares. The line joining the two points chosen upon the wall of the ventricle may run either transversely (parallel with the auriculo-ventricular sulcus), or at right angles to this, or obliquely, as may be desired. The instrument is represented in Fig. 3. A light vulcanite rod, *a*, is slung on a gimbal joint, so that its lower end can move freely in any desired direction in both horizontal dimensions. The lower end of this light rod (which is about nine inches long) can oscillate freely round the point, *b*, where a small hole is bored, at the centre of movement of the vertical rod. The lower end of the latter is tied to any desired part of the surface of the heart by means of a stitch of strong silk, which has been passed under a portion of the visceral pericardium, and through a hole made to receive it at the end of the rod. Near the lower end of the rod, *a*, there is a sliding collar which can be fixed by means of a thumb-screw, and which carries a light rod, *c*, made of stocking wire (steel), and this can glide freely backwards and forwards in the guide, *d*. One end of the steel rod is hooked so that it can be fixed in the heart wall at any desired distance from the end of the rod, *a*; from the other end of the steel wire, a silk thread is carried horizontally to a minute pulley, whose axis coincides with the axis on which the guide, *d*, is slung, and from this pulley the thread is carried up to the hole at *b*, from which it passes to the recording lever. By means of a spiral watch-spring, attached to the axis of this lever, which can be tightened or slackened at will, the lever is made to pull the thread upwards, and so pushes *gently* apart the end of the vulcanite rod, *a*, and the part on which the hook of the rod, *c*, is fixed. On the contraction of the heart taking place, the steel wire, *c*, glides in the guide to an extent corresponding with the shortening of the distance between the end of the rod, *a*, and the hook, the recording lever being pulled down to a corresponding extent. The spring on the recording lever is tightened just enough to keep the silk thread always taut. The lower part of the collar on which the guide, *d*, is slung, can rotate freely, round the rod, *a*, so that the hook of *c* can describe any portion of a circle round the rod, *a*, without causing any pull on the lever, while the heart, as a whole, may move up and down, or from side to side, or twist freely without causing any change in the position of the lever by such movements, seeing that the thread passes through the hole at *b*, which is in the axis of the movements of the instrument, and it is only when the distance between the end of the rod, *a*, and the hooked end of *c* increases or diminishes that the lever moves up or down.

For simplicity sake we have shown the instrument as fitted up for taking a single myographic curve only. When it is desired to take simultaneous tracings of an auricle and ventricle, or of both ventricles, another brass collar, guide, steel wire and thread are attached to the vertical rod, this second thread passing also through the hole at *b*, leading to a second recording lever placed above or below the first. The end of the rod *a* is attached to the visceral pericardium over the auriculo-ventricular sulcus when it is desired to take simultaneous tracings of auricle and ventricle, and over the interventricular sulcus for tracings of the two ventricles.

Care must be taken to keep the surface of the heart moist with normal saline solution, and to arrange the instrument so that it will not be affected by the expansions and contractions of the lungs. The apparatus is very easy to use, and does not appear to cause any change in the force, frequence, or character of the heart-beat.

The first instrument that we employed in order to record the movements of the Mammalian heart was similar in principle to those used by McWILLIAM, FRANÇOIS FRANCK, and others, consisting of a button pressed lightly by a spring on the surface of the ventricles, connected by a system of tambours and india-rubber tubes with a recording lever. This method we did not find satisfactory, the character of the curves obtained being fundamentally altered by comparatively slight changes of the pressure exerted by the button upon the heart, by changes in the diameter of the organ, and also by changes in the pressure of the blood within either ventricle. We do not, therefore, lay any weight upon observations made by such a method unless they have been controlled by the employment of more accurate recording instruments. We doubt whether those who have published observations made by this method are aware how exceedingly untrustworthy it is.

We have not in the following pages thought it necessary to refer to observations on the strength of the ventricular contractions which have been made by others or by ourselves, by means of "button cardiographs." The untrustworthiness of the method was pointed out many years ago by LUDWIG and HOFFA.*

We have made a few experiments upon the hearts of Rabbits, Cats, and Goats, but in the vast majority of cases our observations have been made upon the Dog's heart. We may repeat that we have always employed chloroform, ether, or morphia, or a combination of these throughout our experiments, so that, to the best of our belief, the animals have never at any time been subjected to pain.†

SECTION III.—GENERAL CONSIDERATIONS UPON THE MECHANICS OF THE HEART.

In drawing conclusions from the data obtained by the application of instruments such as those described above, and indeed of any form of cardiograph, it is important to keep in mind certain elements of the mechanics of the heart. It must, in the first place, be admitted that the ventricles, which we have mainly to consider, have not a definite or recognised geometrical shape. Nevertheless, in order to place the matter in a position in which it can be dealt with by the mathematician, we may regard them as two spheres. It is true that, for certain special reasons, connected mainly,

* 'Zeitsch. f. rationelle Medizin,' vol. 9, 1850, p. 116.

† As, in the following pages, we do not touch on the Comparative Physiology of the Heart, we make no reference to the observations of others or of ourselves on the physiology of the hearts of cold-blooded animals. In the case of the Mammalian heart we refer only to such observations as have a direct connection with such parts of the subject as have been dealt with by ourselves, omitting any reference to published experiments made by methods which we know to be untrustworthy.

we believe, with the part played by the papillary muscles, and the juxtaposition of the two ventricles, their form is not that of a true sphere, but it does, we think, sufficiently approximate to that to justify us in approaching the subject from this standpoint. The ventricles, then, may be regarded as hollow muscles of a more or less spherical shape, whose degree of expansion in diastole and contraction in systole can, as we have shown elsewhere,* vary within fairly wide limits. What we have to say upon this subject applies equally to both ventricles.

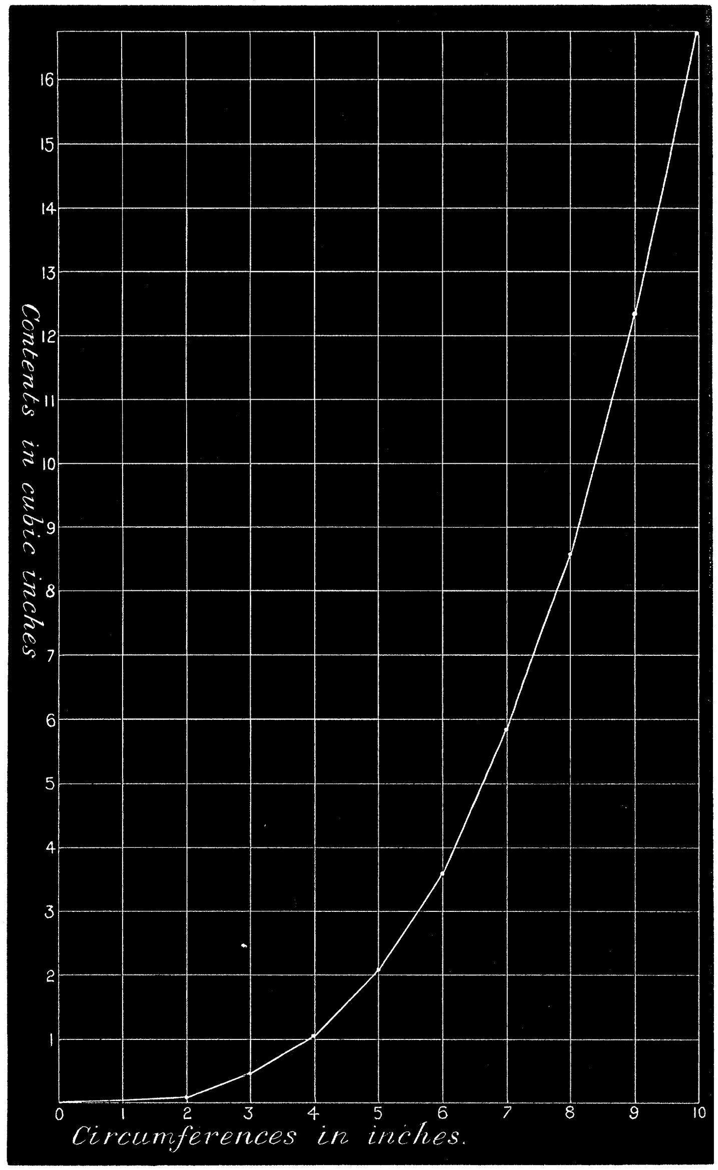
Let us consider, first of all, what is the relation borne by changes in circumference of a sphere to its cubic contents. If the circumference of a sphere increase by equal increments, the increments in cubic contents do not increase in the same ratio, but become relatively greater. If the circumferences be taken as the abscissæ and the corresponding volumes as the ordinates, the curve of volume is what is known to mathematicians as a cubical parabola. When the ventricle expands, the relation between the linear expansion of its walls and the increase in its contents must necessarily bear more or less exactly the relations shown in fig. 4. From this it follows that a given degree of shortening of the fibres of the heart wall, sufficient, let us say, to reduce the circumference of the ventricle by 1 inch, will cause a greater diminution in volume the more dilated the ventricle is at the beginning of its contraction. For example, a diminution of the circumference by 1 inch, of a sphere whose circumference is 10 inches, causes a diminution in the volume equal to 4·5 cubic inches, while a diminution by 1 inch in the circumference of a sphere 5 inches round, causes a diminution of 1·027 cubic inches, although, in the first case, the circumference is reduced only by one-tenth, while in the other case the circumference is reduced by one-fifth. To put the matter conversely, the withdrawal of such a volume of the contents of a sphere, whose circumference is 5 inches, sufficient to reduce that circumference by 1 inch, will cause a reduction of less than a quarter of an inch of the circumference when that circumference is originally 10 inches.

It must be kept in mind, that curves obtained by the myocardiograph show changes in the circumference of the ventricle, and that the changes in volume which result from the contractions and expansions of the heart wall are influenced to an enormous extent by the degree of dilation of the heart. During the dilation, for instance, which results from stimulation of the vagi, a slight shortening of the circumference leads to a relatively very large diminution of the cubic contents of the ventricle, as compared with the reduction in volume which results from an equal shortening of the walls of the undilated ventricle. During the ventricular systole, also, the volume of blood expelled by each unit of contraction of the walls diminishes in the ratio expressed by the curve of fig. 4, that is to say, for each unit of shortening of the ventricular wall at the beginning of systole, when the heart is enlarged, a very much greater quantity of blood is expelled than is the case with each unit of shortening towards the end of systole, at which period the circumference has become much reduced.

* Roy and Adami, "On Overstrain of the Heart," 'Brit. Med. Jnl.,' Dec. 15, 1888.

If we now come to consider the effect of changes of the circumference upon the strain thrown upon the ventricle wall, or, in other words, the resistance to contraction, it is found that, with a given intraventricular pressure the strain upon the ventricle

Fig. 4.



Curve representing the relationship between the circumference of a sphere and its volume, with successive unit increments of circumference.

Ordinates = volume in cubic inches.

Abscissæ = circumference in inches.

wall, that is to say, the resistance to contraction, increases uniformly with the circumference. For instance, the resistance to the contraction of a hollow spherical muscle with circumference of 10 inches and an internal pressure of, let us say, 100 mm.,

Hg, will be twice that offered to the contractions of the walls of a hollow spherical muscle with a circumference of 5 inches and the same internal pressure. It would seem at first sight as if, with this relation between the strain and the circumference on the one hand, and the circumference and volume on the other, the heart must gain in efficiency by becoming expanded, other things, of course, being taken as equal.*

It must be remembered that there is another cause of the resistance to the contractions of the ventricular wall besides those which are directly dependent upon the internal pressure and circumference of the heart wall, and which only comes into play when the ventricular cavity is nearly empty : we refer to the elastic resistance which is offered by the heart wall itself to extreme contraction. To this is due the resilience of the ventricular wall during the early part of diastole, leading to the negative pressure within the ventricles at that period, and which must be looked upon as the giving up again of force employed towards the termination of systole in stretching or compressing some of the elastic components of the ventricle wall.

Before leaving the mechanics of the heart we must say something on the effect on the ventricles of change in the resistance offered to their contractions as a result of rise or fall of the pressure in the aorta or pulmonary artery as the case may be. We will consider mainly the case of the left ventricle, for more is known about changes of pressure in the aorta than in the pulmonary artery. As we have shown elsewhere,† the ventricles normally do not become completely empty at the end of systole. If the pressure in the aorta fall without any change in the force of the contractions of the ventricular wall the ventricle empties itself more completely at each beat, and there is less residual blood. If, on the other hand, the aortic pressure rise, let us say, from 80 to 160 mm. Hg, which is within the normal limits in Man or the Dog, the resistance offered to each contraction will be doubled. (We may exclude for the moment any increase in the force of the ventricular contractions through the medium of the *augmentores cordis* which, as we will presently have to point out, may accom pany rise of arterial pressure, and exclude also the effect of change of pressure in the coronaries on the strength of the heart's contractions.) The increased aortic pressure will necessarily produce the same effect on the ventricle wall which would result from doubling the weight hung on a parallel-fibred voluntary muscle which is being

* On looking more closely into the matter, however, this does not appear to be the case. It would seem that with a given ventricle there is a particular circumference (which will vary with the strength of the contractions), at which the efficiency of the contractions is at its maximum. We have inquired far enough into the physics of a hollow, spherical, contractile shell to learn that the physiology of the heart would gain much were the subject studied by a mathematician who knew the elements of the physiology of voluntary muscles. We have to thank Professor J. J. THOMSON, F.R.S., and Mr. J. DAWSON, M.A., of Christ's College, for having given us much kind help in our studies on the physics of the heart, which we have carried much further than we have thought it desirable to publish here.

† ROY and ADAMI "On Failure of the Heart from Overstrain," *loc. cit.; vide* also JOHANSSON u. TIGERSTEDT "Ueber die gegenseitigen Beziehungen des Herzens und der Gefässe," 'Skandinavisches Arch. f. Physiologie,' vol. 2, 1891, p. 409.

stimulated to a series of maximal contractions by single induction shocks, care being taken to prevent the muscle being stretched by the weight when in a relaxed condition. In both cases the shortening in full contraction will be diminished. It will be sufficient for our purpose in the meantime to insist upon the fact that with *increase of aortic pressure there is, other things being equal, an increase in the amount of residual blood.* There is, however, no resulting diminution of the output of the heart within normal limits. The ventricle is so easily distensible in the relaxed condition that it can receive, in most cases, the same amount of blood, in a given time, as before, in addition to the residual blood which remains over at the end of each beat, so that the ventricle contains at the beginning of systole a quantity of blood equal to what would otherwise have entered it from the pulmonary veins, *plus* the residual blood.

The amount of residual blood is, of course, always increased, also, whenever, the aortic pressure remaining constant, the force of the ventricular contractions is reduced from malnutrition or other cause.

The residual blood is, *cœteris paribus,* increased in amount, also, whenever the volume of blood in the ventricle at the end of diastole is from any cause increased. As we have seen, *the strain upon the walls of a sphere or a spheroid increases with its circumference, and, therefore, the resistance to contraction of the heart-wall is increased whenever it becomes dilated.* As we will presently show, in "vagus slowing" of the heart there is usually, if not always, an increase in the amount of residual blood, but this need not mean that the contractions are weakened by vagus action. Other things being equal, with any increase in the volume of blood entering the ventricle during diastole, there must be an increase of the residual blood corresponding in amount with the increase in the resistance to contraction which results from the increase in circumference. As we have shown elsewhere, increasing the amount of blood entering the ventricle by pressing the abdomen or injecting blood into the veins causes a marked increase in the amount of residual blood.*

It only remains for us to add that "failure of the heart," that is, inability of the heart to pass into the aorta all the blood which passes through the tricuspid orifice, *can* only take place when the tricuspid valve is incompetent. In the case of functional incompetence, either of the mitral or the tricuspid valves, this is the result of an excess of the physiological dilation of the ventricles referred to above, the orifices becoming widened to such an extent that the valve flaps no longer suffice to occlude them.

Before proceeding to give in detail the result of our observations, it is necessary to mention, that when in the following pages we refer to "the auricle" or "the

* Our observations on the changes of the contraction-volume and residual blood which result from changes of the pressure in the systemic veins, published in our communication on "Failure of the Heart from Overstrain" (*loc. cit.*), have since been confirmed by JOHANSSON and TIGERSTEDT, 'Skand. Arch. f. Physiologie,' vol. 1, 1889, p. 331.

ventricle," it must be understood that we speak of *both* auricles and *both* ventricles, and that we have convinced ourselves that, in respect to the particular matter treated

Fig. 5.

Cardiometric curve [two-thirds natural size] obtained from fair-sized dog, showing the effect of moderate vagus stimulation upon the volume of the heart. The upper limit of the tracing represents the volume of the organ in systole, the lower that in diastole. At *b*, stimulation of peripheral end of cut R. vagus, the L. being intact. At *c* current slightly increased in intensity. At *d* the stimulation ceased. The tracing shows the great increase in the contraction-volume which accompanies, and goes more or less hand-in-hand with the vagus slowing. The increased expansion of the heart in diastole is well seen. The changes in the volume of the heart at the end of systole which is shown by the upper limit of the tracing show that on the whole, vagus action increases the volume of the organ at the end of systole as well as the end of the diastole. During the first part of the weak excitation, the heart is more completely emptied of blood than before the nerve was stimulated, and a similar reduction of the residual blood took place when the stronger current was first turned on. Had a kymographic tracing been taken simultaneously with this curve, it would have shown that at these times there was a fall of the arterial pressure which by diminishing the resistance to contraction allowed the ventricles to empty themselves more completely. On cessation of the stimulation, the heart at once returns to its previous rate of beat, but it only gradually recovers from the expansion in diastole and systole.

of, the two sides of the heart are affected in the same manner and degree. Also that by the words "diastolic volume" we mean the volume of blood in the cavity of the heart referred to at the *end* of diastole, and that by "residual blood" we mean the

volume of blood which is left in the particular cavity of the heart at the end of the systole.

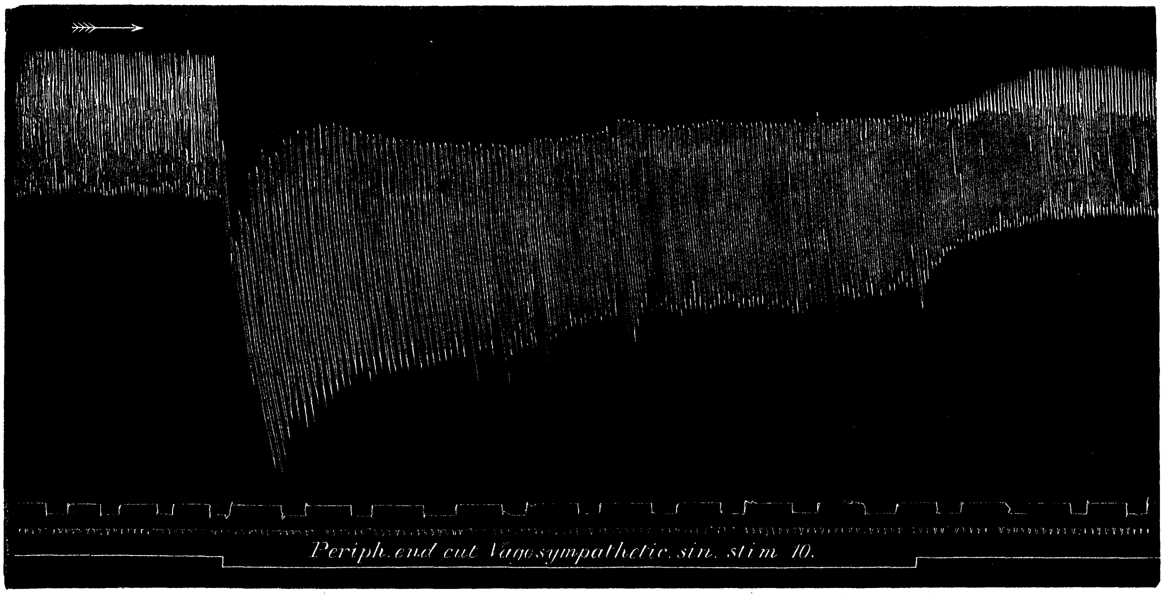
SECTION IV.—ON THE ACTION OF THE VAGUS UPON THE HEART.

A. CARDIOMETER CURVES (Figs. 5 and 6).

(*a.*) *Effect on the Contraction-Volume.*

If, having placed the heart of a Dog in a cardiometer of the kind above described, the peripheral end of one of the cut vago-sympathetics be stimulated by means of an induced current, tracings may be obtained, of which Figs. 5 and 6 are good examples.

Fig. 6.



Cardiometric curve [two-thirds natural size] from small Dog to show the same as Fig. 5. The stimulus is at first more effective than it is later on, its effects gradually diminishing. The upper of the three parallel tracings below is that of the automatic counter, and shows, with the next tracing (that of the seconds' marker), the time necessary for the expulsion of each successive 100 c.cm. of blood from the heart. The effect of the excitation is to cause increase of the contraction-volume which looks at first sight as if it corresponded in degree with the slowing of the rhythm. The automatic "counter" tracings shows, however, that the output is diminished during the period of excitation, and that, therefore, the increase in the contraction-volume is not so great as it should be in order to completely counterbalance the slowing. The increased expansion of the heart in diastole, as shown by the descent of the lower limit of the tracing, as well as the increase in the amount in the residual blood, shown by the lowering of the upper limit of the tracing, are well marked.

In both of these curves the stimulus has not been sufficiently strong to arrest the heart, but only to cause more or less marked slowing of the rhythm. In the case of Fig. 5, part of the curve, from a to b, shows the changes in volume of the heart

at each contraction before the stimulus was applied to the nerve, at *b* the nerve was stimulated, from *b* to *c* there was a slight but appreciable slowing of the rhythm, the secondary coil being 9 cm. from the position at which it completely covers the primary coil; from *c* to *d* the current had been strengthened by moving the secondary coil 5 mm. nearer to the primary, and here a more marked slowing was produced, at *d* the stimulation ceased, the heart at once recovering its former rate of beat.

In this tracing, the upper limit of the curve represents graphically the volume of the heart at the end of systole, while the lower edge of the tracing gives its volume at the end of the diastole, each upward movement of the lever point corresponding to the evacuation of the contents of the ventricles, and each downstroke being equivalent to the diastolic filling of the heart. The length of each up-stroke, therefore, corresponds with the volume of blood expelled from the heart at each contraction, and represents graphically what STOLNIKOW* has termed the "contraction-volume."

In Fig. 6, which also shows the effect of vagus stimulations upon the volume of the heart, the output is recorded automatically by means of the gauge above described, so that it is a very simple matter indeed to learn the effect on the output of the heart of stimulation of the peripheral end of one of the vago-sympathetics.

Taking first of all the contraction-volume, it can be seen that in fig. 5 this is increased from an average of 55 mm. before the stimulus is applied to one of 66 with weak stimulus (*b* to *c*), and to one of 81 with the stronger (*c* to *d*).† In the case of Fig. 6 there is an increase in extent, as measured upon the original tracing, from 27 mm. before stimulation, to 52 during stimulation; the contraction-volume afterwards diminishing during the continuance of the stimulation, this diminution going hand in hand with a gradual increase in the rate of beat. That is to say, the stimulus applied is here less effective.

Both Fig. 5 and Fig. 6 show that the contraction-volume may be nearly doubled by vagus excitation, but with greater slowing the amount of blood expelled at each beat may be trebled or quadrupled or increased yet further as a result of vagus stimulation. (To economise space we do not reproduce curves showing these great increments of the contraction-volume.) As is shown by the curves this increase in the contraction-volume is rendered possible by a more than correspondingly great increase in the diastolic volume. We will presently consider the nature of this increase in the capacity of the heart.

These curves, then, show that, associated with the diminution in rate which results from the action of the vagus upon the heart, there is an increase in the contraction-volume, an increase which is greater the greater the slowing. This effect of change of the rate of beat of the heart upon the contraction-volume is found to take place, other things being equal, whenever the rhythm of the heart varies. Our results so far

* *Loc. cit.*

† These measurements are from the original tracing which has been reduced in size for convenience in publication.

seem at first sight to correspond with those of HOWELL and DONALDSON* and of STOLNIKOW.†

(b.) *Effect of the Vagus on the Output of the Heart.*

But did an exact inverse relationship hold good between the slowing of rhythm caused by vagus excitation and the contraction-volume, the output of the heart ought not to be changed by moderate stimulation of this nerve. Figs. 5 and 6 give the impression that the output of the heart is undiminished by vagus action; more careful examination shows that this is not the case, and that even with such weak vagus stimulation as is shown in these tracings, the output of the heart is lowered. For example, in Fig. 6, the automatic gauge tracing shows that while, before vagus stimulation, 8 seconds were required for the expulsion of every 100 c.cm. of blood, during stimulation 10 seconds were requisite to expel the same amount; in other words, the output was reduced by about 20 per cent. In our other experiments we have likewise found a diminution varying in degree according to the amount of slowing, and we are able to say that moderate excitation of the vagus may lead to a diminution of the output of the heart, which may, in extreme cases, be as much as 30 per cent., or more, according to the degree of slowing, of the output previous to stimulation. It need hardly be said that with a current sufficiently strong to stop the heart, the output of the organ may be completely arrested—at least, for a time. It must, however, be understood that we are at present confining our remarks to such variations in the action of the vagus as are most commonly met with in the normal intact animal.

To summarise, we may say that *the general rule that the contraction volume of the ventricles is in inverse proportion to the rapidity of beat,*‡ *is not completely correct for slowing produced by vagus excitation, for, with this, there is a lowering of the output, which may be as much as* 30 *or* 35 *per cent., or more, although it is usually less than this.*

Our conclusions in this respect agree, on the whole, with those of STOLNIKOW, except that our experiments gave more constant results than seem to have occurred in his observations, which were however comparatively few in number.

* HOWELL and DONALDSON, 'Philosophical Transactions,' 1884, Pt. 1, p. 139.

† STOLNIKOW, *loc. cit.*

‡ We do not find that this rule is more than a very rough one; the resistance to distension of the relaxed ventricle is not by any means a negligeable quantity. [If the wall of the right ventricle offered no resistance to the entry of blood into its cavity during diastole this rule would be an exact one, and it is sufficiently nearly true, as things stand, to be very important. The resistance to distension of the wall of the right ventricle increases disproportionately to the amount of blood contained in it, and with great variations of the rate of beat, the rule is by no means exact, while, with slight changes in the rapidity of the heart's beat, the rule is so nearly correct that it is only by careful measurement that the output can be shown to be different from what it should be according to the rule.]

(c.) *Effect of the Vagus on the Amount of Residual Blood.*

The curve of Fig. 5 is a very exceptional one, in so far that during the first part of the period of stimulation (immediately after the point *b*) the volume of the heart is slightly less at the end of systole than it was before the stimulation. During this part of the curve, the heart might be supposed at first sight to be contracting more powerfully than before the vagus was excited, causing that diminution of the volume of residual blood which, the tracing shows, was produced at this point. This conclusion by no means follows, for, as we have pointed out, the degree of contraction of the ventricles in systole is influenced very much by any change in the blood-pressure in the aortic and pulmonary artery, and the slight diminution of the volume of the heart at the end of systole in this case is, in all probability, due to the fall of pressure in the systemic and pulmonary arteries which usually results from vagus excitation.

After this first diminution of the residual blood in Fig. 5, and throughout the whole duration of the excitation in Fig. 6, and in practically all our other experiments, there is a well-marked increase in the volume of the heart at the end of systole. In other words, the amount of residual blood contained in the heart at the end of systole is increased. This increase in the residual blood may be so great that, as can be seen at one part of Fig. 6, the volume of the heart at the end of systole may be greater than was the volume of the organ at the end of diastole before the vagus nerve had been excited. As we will presently show, this increase in the amount of residual blood during vagus action is due entirely to the ventricles contracting less completely, and not to the auricles containing more blood at the end of the ventricular systole. It does not involve the assumption that the ventricular contractions have been weakened by the action of the vagus, but may be completely explained without any such assumption.

B. Myocardiographic Records of Vagus Action (Figs. 7–12).

Let us now pass on to consider what information regarding vagus action on the heart is to be gained from myocardiographic tracings. Figs. 7–12 are all records of the contractions of the walls of the left auricle and ventricle respectively, and show the effects of vagus excitation. These differ from our first two tracings in that, in all of them, contraction causes the lever-point to descend, and not to ascend, so that the *lower* margin of the curves shows the degree of contraction at the *end* of *systole* of the auricle and ventricle respectively, while the *upper* margin represents the degree to which the walls have expanded at the *end* of *diastole*. In Figs. 7 and 8 the auricular tracing is uppermost, while in Figs. 9–12 it is below the ventricular curve.

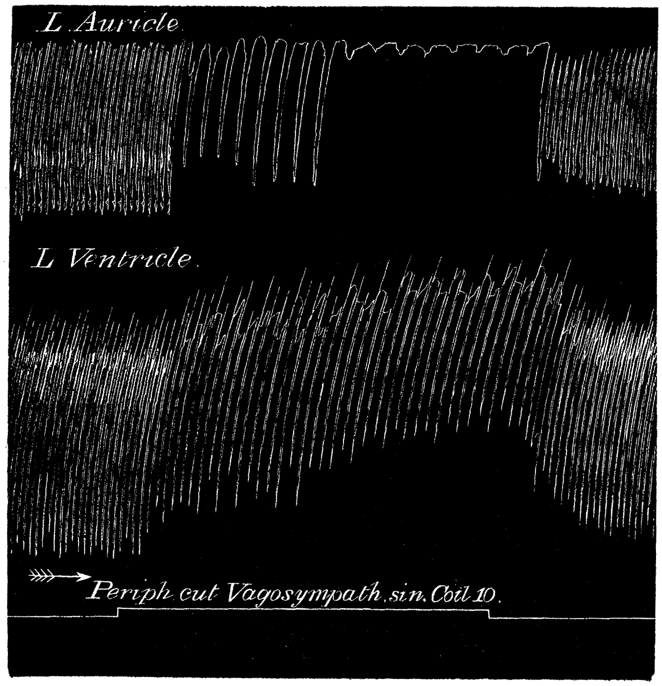
In Fig. 8 the central end of one cut vagus was stimulated, the nerve of the other end being intact. In Figs. 7, 9, 10, and 11 the peripheral end of one of the cut vago-

sympathetics in the neck was excited, while in Fig. 12 the vagus mechanism was called into activity by muscarin, and soon afterwards this mechanism was paralysed by injecting atropin.

I. *Influence of the Vagus on the Auricles* (figs. 7–12).

In all these tracings the auricular contractions are affected to a marked degree as a result of vagus stimulation. In all of them the degree of shortening of the fibres in systole is reduced. In Figs. 8 and 11 this reduction in force is very marked, while in Figs. 7 and 12 the auricular beats have entirely ceased. The curves show, moreover, that the effect of the vagus on the force of the auricular contractions has no very

Fig. 7.



Myocardiographic tracings [one-half real size] from L. Auricle (above) and L. Ventricle (below). Moderate excitation of peripheral end of the cut left Vagus.

In this and in the following curves, unless stated otherwise, contraction of the muscle wall of both auricle and ventricle caused *descent* of the lever point.

The auricular beats are at first weakened, but not greatly so, this being followed by complete arrest of the auricular contractions. [The slight movements of the auricular lever point during the second half of the stimulation were due to the movements of the ventricle, the vertical rod of the myocardiograph being fixed a little below the auriculo-ventricular sulcus in order to avoid the large coronary vessels.] The auricular beats during the first half of the excitation are one-half the rate of the corresponding ventricular beats.

The ventricular tracing shows expansion of the ventricle both in systole and in diastole, the degree of both corresponding with what is shown in such a cardiometer tracing as that of Fig. 6. The auricles take little or no part in the dilation of the heart during vagus excitation. In this case the ventricles began to beat with their own rhythm as soon as the excitation was commenced.

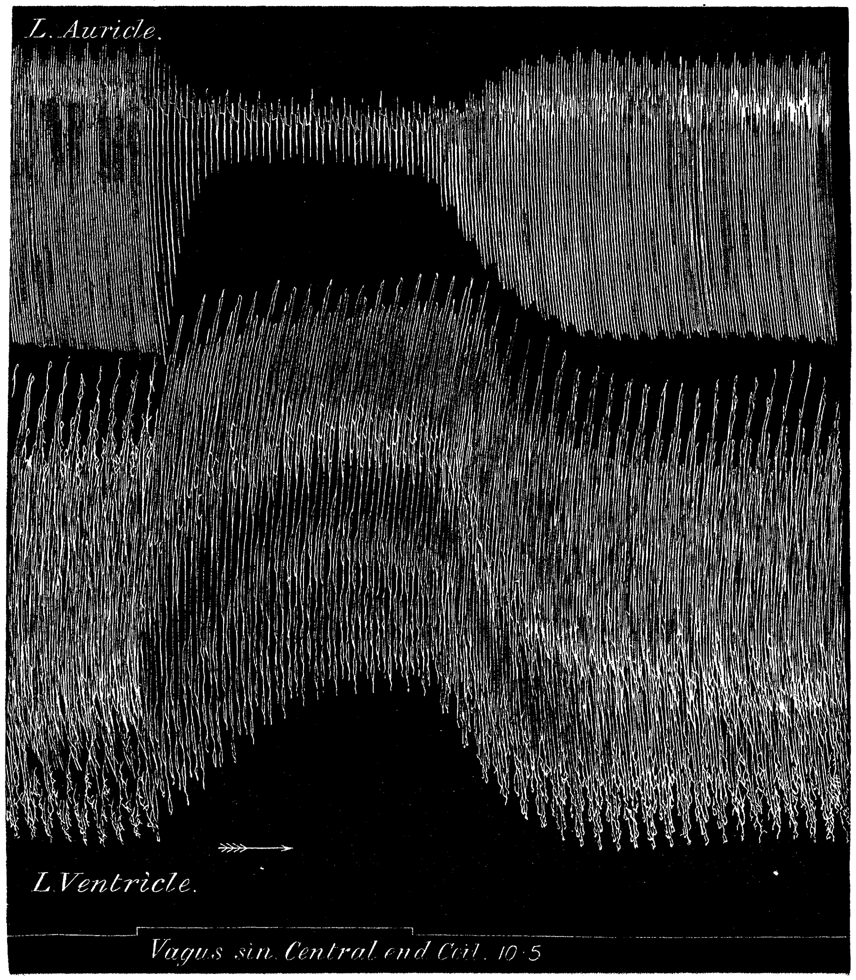
evident relation to the degree of slowing of the rhythm which is produced at the same time. In tracings 8 and 11, for instance, there is no great slowing of the rate of heart-beat, but there is very great weakening of the auricular contractions. In Figs. 8 and 11, again, it can be seen that, on cessation of the stimulus, the slowing disappears much more rapidly than the diminution of the force of the auricular contractions. The diminution of the force of the auricular contractions as a result of vagus action is not preceded by any increase in the force of the beats. It is a primary effect, and is present when the stimuli applied to the nerve are so weak that the slowing can only be recognised by carefully measuring out the tracings. It is produced, like the other vagus effects on the heart which will be dealt with in this section, by reflex, as well as by direct, stimulation of the nerve, by stimulation of the vagus centre in the medulla, or by stimulation of the vagus mechanism in the heart itself by means of such drugs as muscarin, as is well shown in Fig. 12.

When the vagus excitation is powerful, complete arrest of the auricles is produced, as can be seen in Figs. 7 and 12; and such strong stimulation, however produced—whether by direct or by reflex excitation of the nerve trunk, or, as with muscarin, by stimulation of the vagus centre in the heart itself—may cause complete arrest of the auricles for hours, and apparently, for as long a time as the excitation is continued. In some instances, as in Fig. 12, this complete arrest of the auricular contractions is led up to by progressive weakening of the beats, and followed, on cessation of the stimulus, by progressive strengthening. This, however, is not by any means always the case. In Fig. 7, for example, where during the first part of the stimulation the auricular beats are slowed and weakened, there is no gradation in the weakening leading up to the complete stoppage which shows itself during the latter part of the period of stimulation. The auricular contractions which immediately precede the arrest are fairly strong. Something of the same kind can be seen in Fig. 9. We do not see that it is possible to avoid the conclusion that in such cases as those of Figs. 7 and 9 the cessation of the auricular contractions is due, not to a diminution of the contractility of the muscular fibres, but to a diminution either of the excitability of these fibres, or of the strength of the stimuli which reach them before each contraction. As was shown first, we believe, by NUËL,* during strong vagus action the auricle does not respond to stimuli applied directly to its walls, although the ventricle responds readily under similar conditions. This experiment does not enable us to say, however, whether or not the arrest of the auricle by the vagus is due to diminution of its contractility only. In Fig. 12, for example, no excitation applied to the auricle during its period of arrest would have caused it to contract—its fibres had temporarily lost the power to do so. In the case, on the other hand, of the heart, from which Fig. 7 was taken, the auricle during the vagus excitation had not lost the power, and stimulation of its wall during the period of arrest, [as we know from other

* NUËL, "Over den Invloed van Vagusprikkeling," 'Onderzoekingen ged. in het Physiolog. Lab. d. Utrecht'sche Hoogeschool.,' Derde Reeks, vol. 2, 1873.

experiments,] would have caused it to contract, and the arrest, therefore, which that curve shows, must be due either to a diminution of the excitability (under which term we include conductivity) of its fibres or to a lowering of the strength of the rhythmic excitations which reach it from above.

Fig. 8.



Myocardiographic tracings, [original size], as in Fig. 7, save that here the *central* end of the cut left Vagus has been stimulated.

[The auricular beats are markedly weakened by the vagus excitation, but not sufficiently so as to cause the ventricles to cease to follow them, and there is no want of co-ordination in the auricular and ventricular beats. The ventricle shows expansion in both diastole and systole. In this case a part of the ventricular expansion is in all probability due to a rise of the arterial pressure, as is well shown in the tracings in Fig. 23, where a blood-pressure curve was recorded simultaneously with the myocardiographic tracings.]

To summarise we may say *that vagus activity, however called into play, causes a reduction in the force of the auricular contractions and may cause complete arrest of the beats of this part of the heart; that this weakening of the beats has*

an evident relation in degree to the strength of the stimulus employed, but has no direct connection with the degree of slowing of the rhythm which is also produced by the excitation, and that the arrest of the auricles which results from strong vagus action may have two causes, viz.: (a) *Annihilation of the contractibility, and* (b) *diminution either of the excitability of the auricles or of the strength of the excitations which normally reach the auricles from the sinus.*

It may be added that none of the Figs. 7–12 show any increased diastolic expansion of the auricle as a result of vagus stimulation. The increase in volume of the heart during vagus stimulation, which is shown by the cardiometer, is not, therefore, due to the auricles being more expanded in diastole. Some of the tracings, indeed, appear to show a diminished expansion in diastole, but as these curves were obtained by some of our earlier and more rudimentary forms of myocardiograph we do not attach any weight to them in this connection.

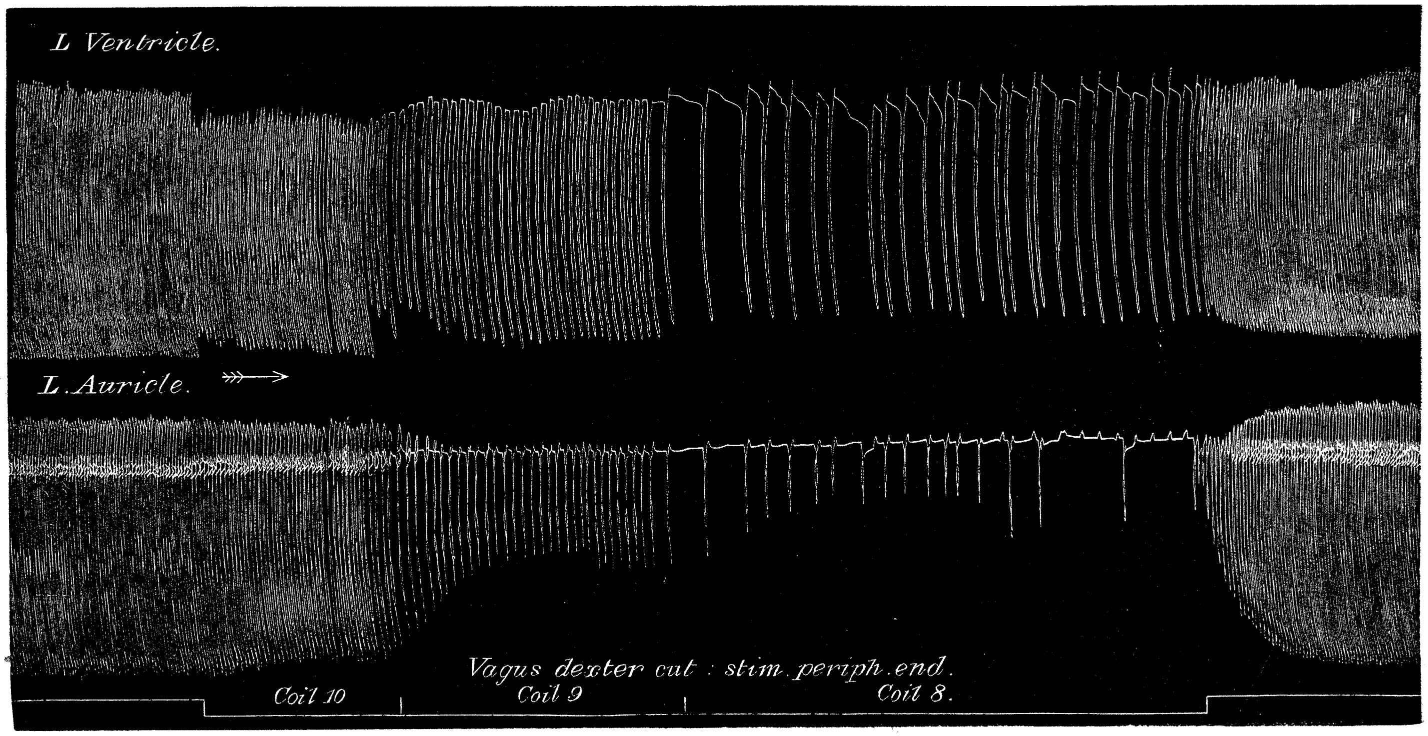
II. *Influence of the Vagus on the Ventricles* (Figs. 7–12).

(*a.*) *The strength of their contractions.*

As we have already said something on the subject, let us take first of all the effect of the vagus on the strength of the ventricular contractions. In all of these figures there is a rise of the lower or systolic margin of the ventricular tracing, which is well marked in Figs. 7, and 8, and 12, while it is very slight, although unmistakably present, in Figs. 9, 10, and 11. There is no doubt therefore that the ventricular wall contracted less completely during vagus excitation in these cases. Our myocardiographic curves agree fully therefore with those obtained with the cardiometer, which show that the amount of residual blood in the ventricles is increased by vagus action. Now, does this less complete emptying of the ventricle imply that the force of the ventricular contractions is diminished by vagus action? It certainly would, if other things could be taken as equal, which, however, is by no means the case. The slowing of the rate of heart-beat which results from vagus action affects the ventricles in a manner which has apparently been overlooked in this connection by those authors, who like FRANÇOIS-FRANCK, McWILLIAM, and others, from observations made by button cardiographs, have concluded that the vagus weakens the ventricles.

Vagus slowing is accompanied by increased contraction volume, and the work done during each systole is correspondingly increased for, we need hardly repeat that the work performed during each ventricular contraction can be expressed numerically by product of the quantity of blood expelled and the hydrostatic pressure in the pulmonary and systemic arteries. With regard, first of all, to the contraction-volume, this, as we have seen, may be doubled or trebled by moderate vagus excitation. With regard to the pressure in the aorta, this is but little reduced in the systemic vessels by such weak vagus action as we are here considering. (The fall in the aortic pressure, it may be noted in passing, which is produced by peripheral excitation of

Fig. 9.



Myocardiographic tracings [two-thirds original size] from L. Ventricle (above) and L. Auricle (below). Stimulation of peripheral end of cut left Vagus. Current gradually increased in strength. This curve shows the ideo-ventricular rhythm beginning when the strength of current reaches a certain point. At one point there is interference of the sinus and ideo-ventricular rhythms, producing bigeminal beats of the ventricle.

[The ventricular tracing shows only very slight diminution in the extent of the contractions, and only slight increase in the diastolic dilation. During the first part of the excitation there is no want of co-ordination between the auricular and ventricular beats, and it is only when a fairly strong current is turned on that the ventricle begins to take on the ideo-ventricular rhythm.

The auricular contractions are markedly weakened, but are throughout followed by ventricular contractions, and it is the great slowing of the auricular beats, and not their weakening, which, in this case, allows the ventricular rhythm to show itself. During the vagus excitation there is diminution in the extent of the expansion of the auricle, as shown by the lowering of the upper limit of the tracing.]

the vagus nerve, is evidently due to the diminution of the output of the heart which we have referred to above.) The lowering of the aortic pressure, which will diminish to a corresponding extent the work thrown on the left ventricle, is, in the vast majority of cases, too slight to counterbalance the increase in the work done during each systole as a result of the greatly increased volume of blood to be expelled. (An exception to this rule is shown in one part of Fig. 5.) The question is, whether the increase in the work done at each ventricular contraction suffices to explain fully the increase in the amount of residual blood, or in other words, the less complete contraction of ventricle which shows itself during vagus excitation. We have the following reasons for answering this question in the affirmative :—

First. The increase in the residual blood corresponds with the degree of increase of the contraction-volume. They go hand in hand, which they would not do if the increase of the residual blood were due to weakening of the ventricular contraction, unless such weakening corresponded in degree with the amount of slowing. This, as we have seen, is not the case with the auricle, and it, therefore, presumably would not be the case with the ventricle.

Secondly. Increase of the contraction-volume from rise of pressure in the systemic veins, produced independently of any vagus action, *e.g.*, by intra-venous injection of blood, or normal salt solution, or by moderate abdominal compression, causes an increase of the residual blood, and the relation in degree between the two is, according to our experience, the same as that in the case of vagus action.

Thirdly. Because we do not lay any weight whatever on our own observations or on those of others upon the strength of the ventricular contractions which have been made with the help of a "button cardiograph," and from which alone it has been concluded that the ventricular contractions in the Mammalian heart are weakened by the excitation of the vagus nerve.

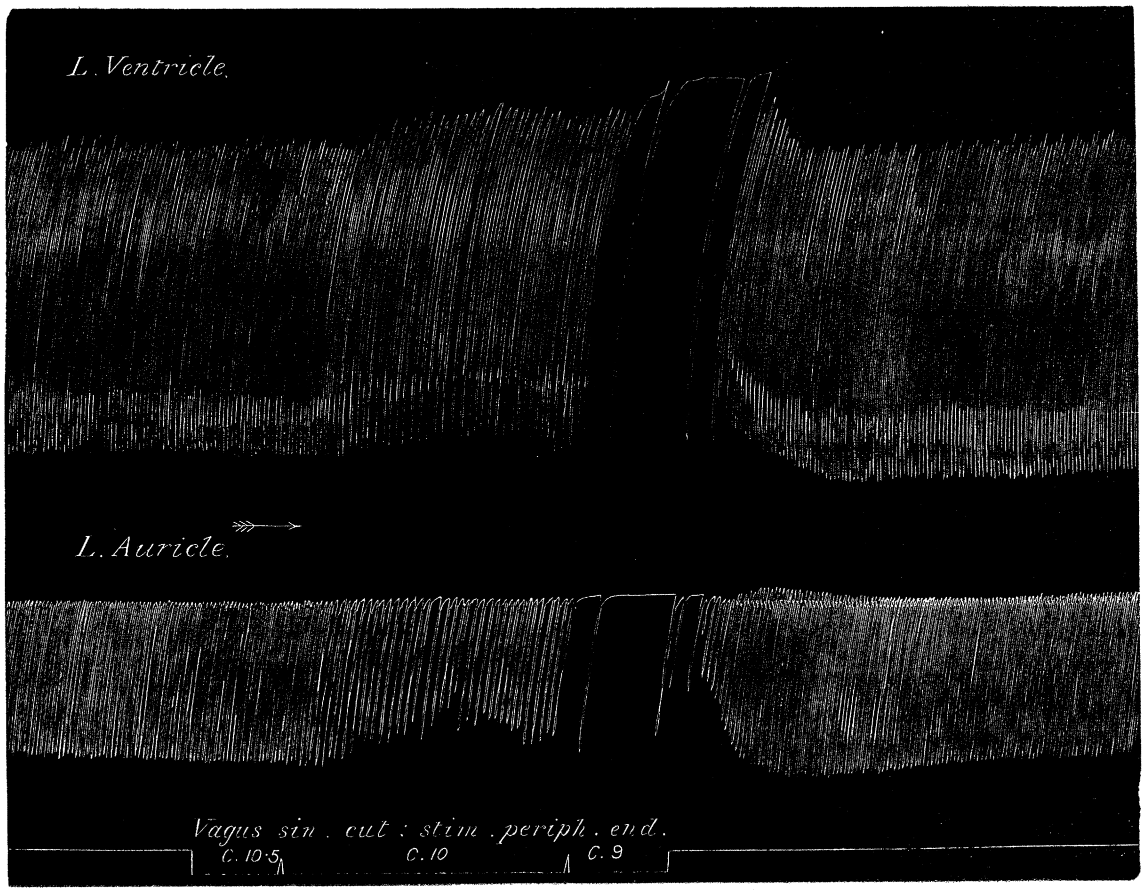
Fourthly. Because no matter how strongly the vagus be stimulated, the lessened shortening of the ventricular fibres is limited in amount (we will presently refer to certain cases of irregularity in which the systolic contraction is confined to one part of the ventricle, and in which the contractions may appear to be very greatly reduced in force). This is quite different from what we find in the action of the vagus on the ventricle of the Frog or Toad, and different also from the action of the vagus on the Mammalian auricle.

We conclude, therefore, that *the less complete systolic shortening of the ventricular fibres, which is produced by vagus action, is not due to any weakening of the ventricular contractions, but is due entirely to the more distended condition of the ventricles and increased contraction-volume, and that the observations on which the contrary conclusion is based were made by untrustworthy methods.*

(*b.*) *Effects of the vagus on the diastolic capacity of the ventricles.*

In all the Figs. 7 to 12, the upper or diastolic limit of the ventricular record is raised during the period of vagus excitation, although in some (Figs. 9 and 12) this elevation is slight. This increase in the diastolic expansion has about the same linear extent as has the decrease in the systolic contractions, or in other words, the upper diastolic margin of the curve and the lower systolic margin are raised to about the same extent. It must, however, be kept in mind, that a given degree of

Fig 10.



Myocardiographic tracings [original size] from L. Ventricle (above) and L. Auricle (below). Stimulation of peripheral end of cut left vagus with, as in Fig. 9, gradually increasing current, but here a certain amount of after effect [increased strength of beat] is observable in the auricular contractions. The auricular contractions are not very greatly weakened and the ventricular beats follow them without any appearance of the ideo-ventricular rhythm. Towards the end of the excitation the ventricle does not respond to some of the auricular beats.

linear expansion of the wall of the distended ventricle, involves a very much greater addition to the cubic contents of the ventricle than will result from the same expansion of the heart wall at the end of systole, when this chamber of the heart is very much smaller. We need not repeat what we have said on this subject in Section III.,

and need only note that there is no want of accordance between our cardiometer and myocardiographic curves, with regard to the effect of the vagus nerve on the degree of diastolic expansion of the ventricles.

As we have noticed above, the very great increase in the contraction-volume of the ventricles is accompanied, and rendered possible, by relatively still greater diastolic expansion. How is this great ventricular distension produced? As the curves of Figs. 7 to 12 show, it is not due to one of the factors, viz., the auricular contractions, by which the ventricles are usually distended. The auricles are either weakened or arrested, as we have seen, by vagus action. We can, therefore, say that the diastolic expansion in question takes place in spite of the fact that the auricles are weakened.

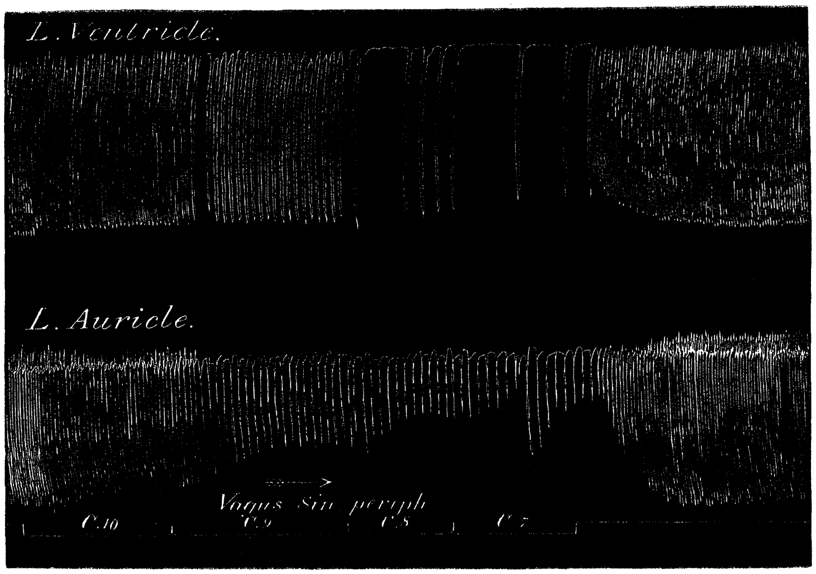
Is it due, as François-Franck, McWilliam, and others have asserted, to a diminution of the tonus of the relaxed ventricular walls? In coming to this conclusion these observers omitted to take into consideration one important factor, viz., the intra-ventricular pressure during diastole. It can only be assumed that the tonus, or elasticity as we prefer to call it, of the ventricular walls, has diminished or increased as the case may be, if it can be shown that the degree of expansion of the ventricles has increased or diminished *without any corresponding change in the distending force.* Now the auricular contractions are not the only cause of the diastolic filling of the ventricles. A rise in the pressure of blood in the large veins may have even more effect than changes in the force of the auricular beats. In the case of the thin-walled, extremely distensible right ventricle, any change in the pressure of the blood in the systemic veins causes a great change in the diastolic volume, whether the auricles be beating or not.

Is the hydrostatic pressure in the large systemic veins increased by excitation of the vagus? We have made a sufficient number of experiments to prove that not only is this the case, but also that this rise of the venous pressure goes hand in hand with the slowing of the rate of heart-beat. As an illustration, chosen at random, we found the venous pressure was raised 50 mm. H_2O, by fairly strong vagus stimulation and 80 mm. by stronger, in both cases the heart-beats having been greatly slowed, but not definitely arrested.

There is no doubt, then, that by vagus action the intravenous, and, therefore, intra-ventricular pressure in the right ventricle, during diastole, is increased, and the only question we have to decide is whether this increased pressure be sufficient to cause the great increase in the diastolic volume which is produced by moderate excitation of the vagus. This matter is very easily settled, since we have only to observe what degree of diastolic expansion is produced by a similar rise of the venous pressure produced, without calling the vagus nerve into play. The pressure of the blood in the systemic veins can be raised easily enough by injecting blood or warm salt solution into a vein, and we find that the diastolic distension thereby produced is not less than that which occurs with a similar venous pressure during vagus excitation.

We conclude, therefore, that *the increased diastolic volume of the ventricles during vagus excitation is due to increased intra-ventricular pressure during diastole, and not to any change in the elasticity of the relaxed ventricular wall, and that those observers who have explained this expansion by a change of tonus have been misled by incomplete observations.*

Fig. 11.



Myocardiographic tracing [half original size] from L. Ventricle (above) and L. Auricle (below). Stimulation of peripheral end of cut left vagus with gradually increasing strength of current. The curve shows progressive weakening of auricular contractions, the ventricles ceasing to follow these beats when they become weakened beyond a certain point. At one point the ventricle follows every other beat of the auricle.

(*c.*) *Cause of the rise of venous pressure during vagus excitations.*

The explanation of this seems very obvious to us now, but it took us a deal of trouble before we were able to clear the matter up completely. In the first place, it is not due to any increase in the volume of blood which comes from the abdominal viscera, and which might have caused it by the vagus diminishing the volume of blood contained in them at any given moment. This was easy enough to settle by cutting the vagi and splanchnics above the diaphragm, which made, however, no change in the effect of vagus stimulation on the venous pressure. So soon as we had satisfied ourselves of this, and also that the output of the heart is diminished by vagus action, the matter was clear enough. Diminution of the output of the heart means a corresponding diminution of the inflow into the right ventricle. If less blood leave the large veins without a corresponding fall in the amount which enters them from the capillaries, the venous pressure must necessarily rise.

There is another possible explanation, viz., that the rise of intra-venous pressure is due to an active contraction of the walls of the large systemic veins; but, by direct

inspection, it is easy to convince oneself, that these vessels become passively expanded during vagus action as a result of the rise of pressure in their interior. We may conclude, then, that *the pressure in the large systemic veins becomes raised during vagus action, because the quantity of blood which passes from them into the right ventricle (which we may refer to as the "input" of the heart), in a given time, is diminished, and not because of any increased inflow of blood into the veins from the periphery of the body, nor because there is any active contraction of their walls.*

(*d.*) *Cause of the diminished "output" and "input" of the heart during moderate vagus stimulation.*

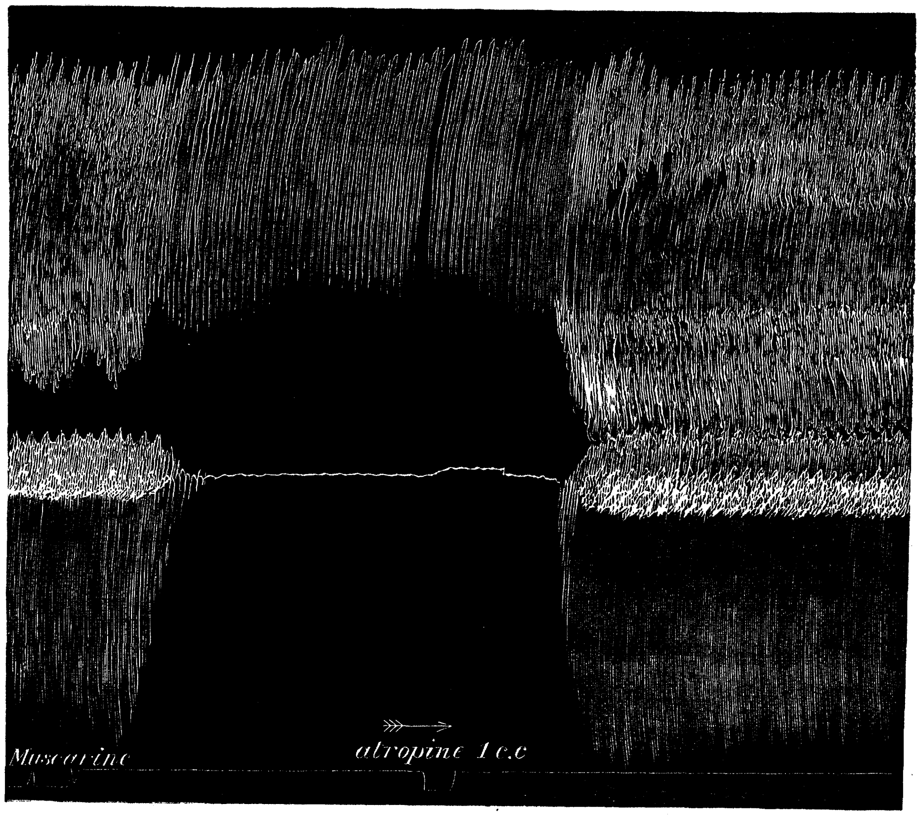
We have pointed out above that the output of the heart is lowered by the action of the vagus, and we have just shown that the "input" is lowered—although, indeed, the first involves the second; and we have now to consider what is the cause of both.

They are not due to any weakening in the contractile power of the ventricles, for, in the first place, as we have shown, there is no such weakening, and, secondly, if there *were* any weakening it would not diminish the output so long as the tricuspid valve remained competent. It need hardly be said, however, that moderate vagus excitation does not cause tricuspid incompetence. *We may safely conclude, therefore, that the fall in the output of the heart during vagus action is due to the diminution of the input of that organ,* so that what we have to consider is the cause of the latter. Now, there are three factors concerned in filling the right ventricle, viz. (*a*) the pressure of the large veins, (*b*) the auricular contractions, and (*c*) the pressure in the ventricular cavity during diastole. The first of these, as we have seen, may be excluded, for vagus action causes a *rise* of the venous pressure. When we come to the effect of the vagus on the auricles, we have evidently to do with one of the causes of diminution of the inflow into the right ventricle. As our curves (Figs. 7–12) show, moderate vagus action weakens or arrests the auricular beats. (It may be noted here that this weakening or arrest of the auricles by vagus action does not go hand in hand with the rise of venous, and therefore of intra-auricular, pressure; so that the diminution in the extent of the auricular contractions which appears in our tracings is not due as might possibly be supposed to increased resistance to their contraction.) Excitation of the vagus causes a primary diminution or annihilation of the auricular contractions, which involves a corresponding interference with the part played by them in filling the ventricles. It is obvious, therefore, that *the diminution of the input of the heart during vagus stimulation is partly, at all events, due to the weakening or arrest of the contractions of the right auricle.*

It is important, however, to note that the power of the vagus mechanism to lower the input, and therefore the output, of the heart by weakening or stopping the auricular beats is limited. Even complete arrest of the auricles does not prevent the inflow of blood from the veins into the ventricles. *Weakening or arrest of the auricular beats, diminishes, but cannot arrest, the inflow to the ventricles.*

As we have pointed out above, the output of the heart may be diminished by some 20 to 30 per cent., more or less, as a result of moderate vagus excitation. When we come to consider the effect of the vagi on the resistance to distension of the ventricular wall, there are one or two matters which must be borne in mind, viz. (*a*) that the elasticity of the relaxed ventricular wall is not changed by vagus action; (*b*) that the amount of residual blood in the ventricles at the end of systole is increased as a

Fig. 12.



Myocardiographic tracing [original size] from L. Ventricle (above) and L. Auricle (below), to show the effects of muscarin followed by atropin. The auricles are brought to a complete standstill by the former, while the ventricles continue with the ideo-ventricular beat. The latter causes resumption of the previous rate of beat with initial augmentation of force of contraction of both auricle and ventricle. [Muscarin does not lower the excitability of the ventricles as does stimulation of the vago-sympathetic trunks, and on cessation of the auricular beats the ventricles at once take on the ideo-ventricular rhythm.]

result of the increased contraction volume; and (*c*) that the slowing of the ventricular rhythm by the vagus increases to a corresponding extent the volume of blood which is available to enter the ventricles during each diastole. The conditions necessarily result in distension of the ventricles during diastole, which will be the greater the greater the slowing. Accompanying this distension, and indeed causing it, there will necessarily be a rise of the intra-ventricular pressure during diastole, as well as a rise of the pressure within the large veins leading to the heart.

It will be observed that this explanation of the rise of venous pressure and the distension of the ventricles during vagus action, if true for the right side of the heart, must also apply to the left heart. The distension of the left ventricle during vagus excitation, in other words, must be accompanied by a rise of pressure in the pulmonary veins. We have to enquire, therefore, whether vagus stimulation causes any such rise. We have been spared the trouble of making the experiments necessary to settle this point, by the kindness of Dr. C. J. MARTIN in placing at our disposal the results of his observations on the subject. We have his permission to state here, that his curves show that, during vagus excitation, the pressure in the pulmonary veins rises to a height corresponding with that which we found to take place in the pressure within the systemic veins under like circumstances.

To summarise, we may say, then, that *the rise of venous pressure during diastole, which is produced by vagus excitation, is a necessary result of the slowing of the rate of heart-beat which indirectly, by increasing the contraction volume, increases the volume of residual blood, and directly increases the volume of blood available for entering the ventricles during each diastole, which necessarily leads to increased resistance to distension of the relaxed ventricular wall, and, also, that this explanation applies equally to the right and the left ventricles.*

(*e.*) *After-effects of vagus excitation on the output of the heart.*

On cessation of the excitation of the nerve the rhythm of the heart very rapidly quickens, and becomes as fast as, or faster than, before the excitation; although, as can be seen in Figs. 5 and 6, the heart more gradually returns to the *volume* it presented before the nerve was excited. During this period it is very usual to find the output of the heart greater than it was before the nerve was stimulated. As examples of this, we give the measurements from two experiments :—

DOG A.

Peripheral end cut *vagus sinistra*, right intact.	Output of heart in 10 secs.	No. of beats in 10 secs.
	c.c.	
Before stimulation	324	28
During ,, ...	281	15
After ,, ...	364	30

DOG B.

Peripheral end cut *vagus sinistra*, nerve of right side being intact.	Output of heart in 10 secs.	No. of beats in 10 secs.
	c.c.	
Before stimulation	309	26·5
During ,, ...	275	17
After ,, ...	344	29

These measurements show a very appreciable after-increase in the output, which lasts for a short time, and which gradually diminishes, until the output is again the same as that before the excitation. Two causes may be assigned to this temporary increase of the output, viz. : 1st, the increased pressure in the large veins, which only gradually falls again on ceasing the stimulation. Of more importance is, 2ndly, the increased force of the auricular beats, which sometimes is a marked after-effect of vagus action. This is shown in the myocardiographic curve from the left auricle in Fig. 12, and it can also be recognised in Fig. 10. These curves show that the weakening or arrest of the auricles by the vagus may be followed by increased force of contraction as an after-effect. This after-effect of vagus action is not by any means a constant phenomenon, and is seldom more markedly present than it is in Fig. 12.

The output of the heart is by no means always increased as an after-effect of vagus excitation. For example, in Fig. 5, there is no increase in the output during the period immediately following the stoppage of the excitation. In some cases, on the other hand, after the heart has begun to beat fast, the output only gradually returns to the value it had before the stimulation was applied.

The explanation of these differences in the after-effects of vagus excitation on the output of the heart is obvious enough on examination of a series of myocardiographic records of the action of the vagus on the auricles. These show that while, in some cases, the auricle has a period of increased force as an after-effect, in other cases the auricle gains strength more slowly, for, as we have pointed out, there is no direct correspondence between the rate of the heart-beat and the strength of the auricular contractions.

We conclude, then, that *the want of conformity in the after-effects of vagus excitation on the output of the heart, is due to variations in the after-effect of the excitation on the auricular beats, and that the temporary increase of the output, which is of common enough occurrence, is due to the temporary increase in the force of the auricular contractions, and also to the fact that the venous pressure usually falls slowly.*

III. Effect of Vagus Excitation on the Rhythm of the Heart.

(*a.*) *Fairly Strong as compared with Moderate Excitation.*

While slight or moderate stimulation of the vagus affects the heart in the manner which we have sought to describe above, stronger stimulation has very different effects, and a study of these is of extreme interest, seeing that we thereby learn how it is that the influence of the nerve on the heart is limited, so that the economy as a whole, is not endangered, even by the most powerful functional activity of the vagus mechanism.

In the first place, when the vagus excitation has reached a certain strength, which varies in different animals, and in the same animal at different times, the ventricles

cease to follow the rhythm of the auricles and begin to beat with a rhythm of their own, which may be perfectly regular, although, when it first commences, it is usually slow and somewhat irregular. This independent ventricular beat is well shown during the whole period of the excitation in Fig. 7, is fairly well seen in Fig. 9 towards the latter part of the period of excitation, and is still better seen in the ventricular tracing of Fig. 12, showing the effect of muscarin on the heart.

We may summarise, then, by saying that *when the vagus excitation exceeds a certain strength, which varies in different cases, the ventricles begin to beat independently of the auricles, and, eventually, with a fairly regular rhythm.*

(*b.*) *On the Independent Ventricular Rhythm.*

It has long been known that the isolated ventricle of cold-blooded animals will, under certain conditions, continue to beat with a regular rhythm. But it is comparatively recently that the isolated Mammalian ventricles have been shown to have also an independent rhythm. This, like so much else in physiology, we owe to C. LUDWIG and his pupils. WOOLDRIDGE,* by means of a cord looped round both auricles, but behind the roots of the aorta and pulmonary artery, found that, on tightening the loop, he could cut off physiologically the auricles from the ventricles without tearing through the visceral pericardium, and that, on removing this ligature, both ventricles and auricles continued their contractions, each, however, with a different rhythm, and that neither vagus nor accelerans had now any influence upon the ventricles, although they continued to affect the auricles in the usual manner. WOOLDRIDGE's method was much improved upon by TIGERSTEDT,† who employed a very ingenious instrument, called by him an "atriotome," which allowed of the ventricles being cut off from the auricles immediately above the auriculo-ventricular sulcus. His observations confirm those of WOOLDRIDGE, namely, that on completely separating the ventricles from their nervous connections with the auricles, the former contract with a rhythmic beat, and possess, therefore, in themselves all that is necessary for rhythmic activity. KRONECKER and SCHMEY‡ have sought to show that this independent ventricular rhythm is due to the action of a centre or centres, situated at the lower margin of the upper third of the inter-ventricular septum. Whatever the exact nature of the mechanism whereby this independent ventricular rhythm is regulated, there can be no doubt of its existence, and, also, that it is usually slower in rate than the sinus or post-auricular rhythm of the ventricles.

It must not be supposed, however, that anatomical separation of the muscular and

* WOOLDRIDGE: DU BOIS-REYMOND'S 'Archiv für Physiologie,' 1883, p. 522.

† TIGERSTEDT, "Ueber die Bedeutung der Vorhöfe für die Rhythmik der Ventrikel des Säugethierherzens," DU BOIS-REYMOND'S 'Archiv,' 1884, p. 497.

‡ KRONECKER and SCHMEY, "Das Coordinationscentrum der Herzkammerbewegungen," 'Sitzungsberichte der Berliner Akademie, Physikalisch-Mathematische Klasse,' 1884, p. 87.

nervous components of the walls of the auricles, at the line where they join the ventricles, is necessary in order to allow this independent ventricular rhythm to show itself.

If we can cut off or weaken the impulses which reach the ventricles from above by excitation of the vagus, a rhythm, having the characters of that described by WOOLDRIDGE and TIGERSTEDT, gradually shows itself. The mere fact that in such cases the ventricular beat does not correspond with that of the auricles indicates that we have here to do with a rhythm which is essentially different from that in which the ventricular systole follows that of the auricles, and it may safely be concluded that we have to do here with the independent ventricular rhythm which shows itself when the ventricles are anatomically or physiologically isolated. There is, however, one important difference between the independent ventricular rhythm which shows itself on excitation of the vagus and that which appears on giving muscarin or in anatomically isolating the ventricles, namely, that, in the first case, the independent rhythm establishes itself slowly, whereas in the other two cases it does not do so, and the causes of this difference we shall now consider.

(c.) *The Excitability of the Ventricles.*

That the vagus has the power of stopping the Mammalian ventricle, even for a few seconds, is explicable, so far as we can see, only by one or other of two hypotheses, namely (*a*) that the independent rhythm of the ventricles takes some little time—a time varying with each heart—to establish itself. This involves the conclusion that the ventricular contractions, due to the intrinsic mechanism of the ventricles, cannot "follow on" the contractions which, previous to the excitation of the nerve, reached the ventricles after each auricular beat, and that the ventricles had, so to speak, to start afresh. (*b*) The second hypothesis is, that the vagus diminishes temporarily the excitability of the ventricles, or of their rhythmic centre, if it exist, so that their independent rhythm does not at once follow on the post-auricular contractions which preceded them.

We know of no facts which tend to support the first of these two explanations, which might seem, *à priori*, the more probable. In favour of the second hypothesis, and against the first, there are certain facts which are too important to be overlooked. In the first place TIGERSTEDT* found, on severing the auricles from the ventricles in Rabbits, by means of his "atriotome," that the ventricles at once pass on to the slowed but regular rhythm which is due to their intrinsic mechanism, and that there is no such temporary arrest of the ventricles as is produced by strong vagus excitation. That the severance of the auricles from the ventricles was complete in his experiment was shown by the fact that, after the atriotome had been applied no further slowing

* TIGERSTEDT: DU BOIS-REYMOND'S 'Archiv für Physiologie,' 1884, p. 497.

of the ventricular beat could be produced by excitation of the vagus. His observations are, therefore, directly opposed to the first of the two above-named hypotheses.

Of even greater importance in this connection, and supplying a direct proof that the second of these hypotheses is the true one, are the observations of EINBRODT* which were published more than thirty years ago. As EINBRODT did not himself draw the conclusion that his experiments prove that the vagus has the power of diminishing the excitability of the ventricles, we think it desirable to give an abstract of his results on the influence of the vagus on the effects of induction currents directly applied to the ventricles.

In the first place, EINBRODT found that, by means of weak induction currents directly applied to the surface of the ventricles, the rhythm of the latter could be made more rapid. For example, in two Dogs he found that, in the one case, the contraction underwent acceleration from about 74 in 30 seconds to about 116 in the same time, while in the second case the quickening was from a mean of 73, without direct stimulation, to 112 with stimulation, and, on repeating the experiment, from 95 to 171 respectively. When he stimulated the vagus and the surface of the ventricles at the same time, he found that the vagus did not arrest the heart, but that the beats were not so rapid as they were before the two excitations were applied. If the ventricles be directly excited, after stimulation of the vagus has already been begun, the acceleration is less than would have resulted from direct excitation alone, and he even found in some cases that the rate of beat, which could be produced by direct excitation of the ventricles, was lower than that before any excitation was applied.

He found, moreover, that he could, in his series of experiments on combined vagus and direct cardiac excitation during vagus stimulation, bring the secondary coil of his arrangement for exciting the ventricles up to 30 mm. of the zero of the scale, before death of the heart resulted, while, in his other series of experiments, without simultaneous excitation of the vagus nerve, death of the Dog's heart ensued as soon as the secondary coil was within 90 mm. of zero.

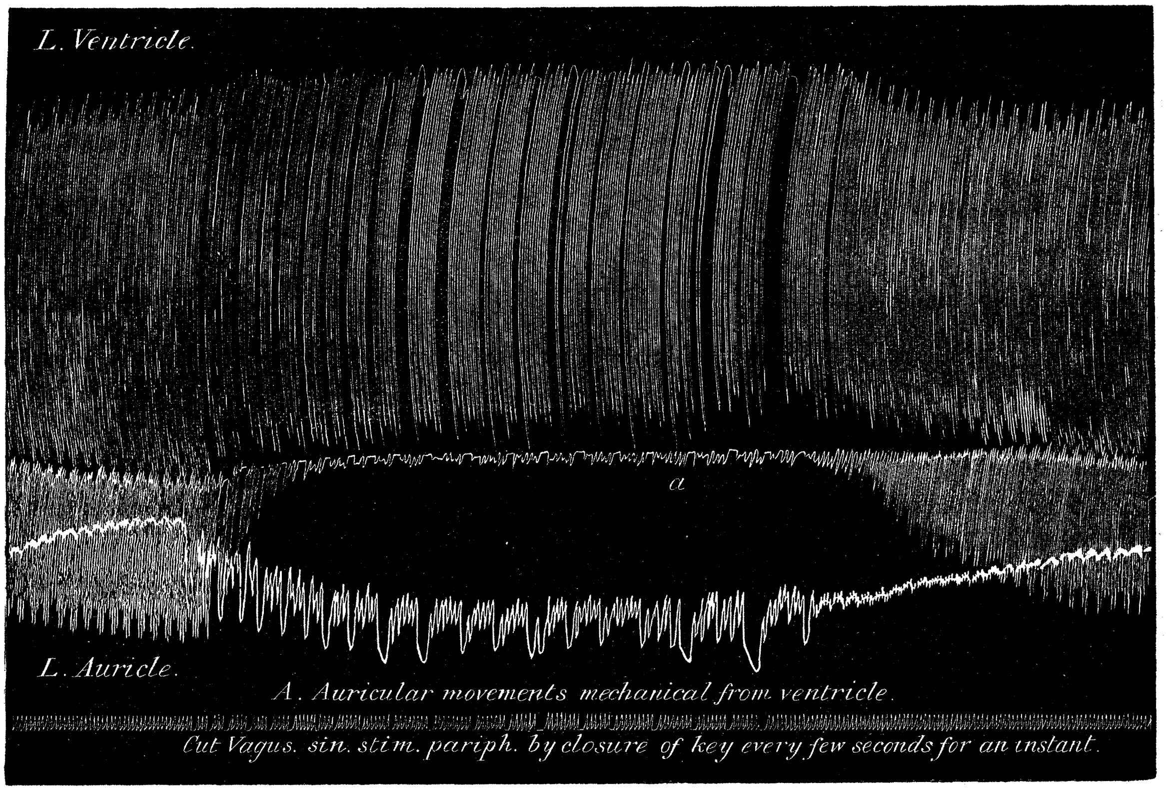
EINBRODT, whose communication was presented by C. LUDWIG, drew such conclusions as were consistent with what was at that time known with regard to the physiology of the heart. We, as already mentioned, look upon them as proving that vagus action lowers the excitability of the ventricles.

In the effects of muscarin on the Mammalian heart we have evidence, as is well shown in Fig. 12, that complete arrest of the auricles, the ventricles being left entirely to their own intrinsic mechanism, does not of itself necessarily cause temporary arrest of the ventricles such as may be produced by strong vagus action. As is shown in the figure, the ventricles at once pass into the slow but regular automatic rhythm, such as TIGERSTEDT obtained on cutting through the auricular walls close to the auriculo-ventricular sulcus. This curve illustrates an important difference between

* EINBRODT, "Ueber Herzreizung und ihr Verhältniss zum Blutdruck"; 'Wiener Sitzungsberichte, Math.-Nat. Klasse,' 1860, vol. 38, p. 345.

muscarin action on the Mammalian heart, and that produced by strong direct or reflex excitation of the vagus nerve, a difference which may be explained on the assumption that muscarin does not excite that part of the vagus mechanism which leads, on vagus excitation, to a lowering of the excitability of the ventricles.

Fig. 13.



Myocardiographic tracings [two-thirds original size] from L. Ventricle (above) and L. Auricle (below). Stimulation of peripheral end of left vagus by induced current applied for a second at successive intervals of 4 to 7 seconds. The interruptions in the time curve show the periods of stimulation. It can be seen that these correspond to intermissions of the ventricular beats. The auricles were completely arrested, (the movements of the recording lever during full vagus action were passive in nature, and due to the pull of the ventricular contractions.) A blood-pressure curve, taken simultaneously, is shown over the auricular tracing. The ventricular tracing shows the ideo-ventricular rhythm with intermissions during the time the current was actually passing through the nerve. The rhythm is otherwise fairly regular. As the blood pressure in the systemic vessels fell somewhat during the excitation, the ventricle does not show great expansion in systole and diastole, but only dilated to such an extent as corresponds with the slowing of the rhythm, the fall in the blood-pressure diminishing somewhat the degree of expansion which is produced by the increased contraction-volume.

If further proof be needed of the existence of this power of the vagus to lower the excitability of the ventricles, it can be supplied by a simple experiment illustrated by Fig. 13. In this experiment the uncut left vagus was stimulated for an instant (about a second) at intervals of about 6 or 7 seconds, a strong induction current being

employed. This intermittent excitation led to complete arrest of the auricles. (We were able to convince ourselves during the experiment that the slight movements of the lever-point in the auricular tracing during vagus action were passive in nature, and caused by the pull of the contracting ventricle.) This intermittent vagus excitation did not, however, arrest the ventricles, except for the instant when the current was actually passing through the nerve. The independent ventricular rhythm established itself without any initial arrest such as is produced by continuous stimulation, and the only result due to the current, so far as the ventricle is concerned, is to cause intermissions of the ventricular rhythm at each successive closure of the key. We can, thus, dissociate, by interrupted excitation, the effect of the vagus on the auricles and on the excitability of the ventricles. To summarise, *discontinuous excitation of the vagi produces continuous effects on the auricles, but discontinuous upon the excitability of the ventricles. In other words, the vagus action on the excitability of the ventricles ceases with cessation of the current.*

We might give further evidence of the fact that vagus excitation lowers the excitability of the ventricle, but imagine that we have in the above supplied sufficient convincing proof of this. We therefore conclude that *vagus stimulation lowers the excitability of the ventricles, so that they are not only less responsive to the weakened stimuli reaching them from above with each auricular beat, but also that their independent rhythm begins more slowly than would otherwise be the case.*

The fact, that continuous strong excitation of the vagi does not arrest the ventricles for more than a limited time, shows that the influence of this nerve in lowering the excitability of the ventricles is not a lasting one. While the excitation is still kept up the excitability of the ventricles after the initial lowering gradually rises, and the ideo-ventricular rhythm gradually shows itself. The influence of the vagi on the excitability of the ventricle differs from their influence on the auricular contractions, which can be inhibited by excitation of these nerves for an indefinitely long time (hours).

As is shown by the curve in Fig. 13 the lowering of the excitability only causes intermissions of the ventricular beats while the current is actually passing through the nerve, disappearing instantly on cessation of the stimulation: differing in this respect also from the effects of the vagi on the strength of the auricular beats.

(*d.*) *Effect on the Heart-Rhythm of Moderately Strong Vagus Excitation.*

We have seen that, with a certain strength of stimulation of the vagi, the ventricles are released more or less completely from its influence (except in so far as their excitability is concerned) and from their association with the auricular beats; but, as we might anticipate, there is a stage of strength of excitation, in which the ventricles are not completely freed from the sinus rhythm, although the excitations from above have been either weakened or slowed enough to allow the independent ventricular rhythm

to come into play. This stage, or gradation, of vagus activity is, according to our experience, a broad one in the Dog. With it there is irregularity in time of the ventricular beats, owing to the interference of the two rhythms, except in such cases as in the tracing in Fig. 7, where the independent ventricular rhythm is twice as quick as that of the auricular beats, or where the auricular beats are twice as fast as the ventricular beats, and where there is only a slight (apparent) irregularity in force (*pulsus alterans*) produced. In other cases there may be any of the other forms of a rhythmic irregularity (*pulsus bigeminus*, *p. trigeminus*, *p. quadrigeminus*, &c.), although an arhythmic irregularity is that most commonly met with.

Irregularity of the heart with a certain degree of vagus activity is a necessary consequence of the arrangement by which the vagus governs the heart. It cannot be called pathological, unless we are to give this name to weak points in physiological arrangements. Like all irregularity it diminishes the efficiency of the heart without reducing the amount of energy expended by the cardiac muscle in a given time. This will not matter very much in healthy people or animals, in whom its occurrence is only of short duration as a rule, and whose hearts have a good "margin of reserve" of power. But in the case of people with heart disease, in whom the vagus is *usually* called into increased activity, it becomes, as we will presently point out, an extremely harmful factor. In Dogs this form of irregularity is more commonly met with under healthy conditions than in the case of any other Mammal with which we are acquainted. So much so that some hold it to be normal in the Dog. It can always be stopped in them by atropin or section of both vagi.

To summarise: the action of the vagus on the cardiac rhythm may be naturally divided into three stages according to the strength of the excitation of the nerve, viz.:

1. *With relatively weak excitation, there is slowing of the rhythm but no irregularity.*

2. *With stronger stimulation the independent ventricular rhythm shows itself, and this, by interference with the ordinary or auricular rhythm, usually leads to irregularity of the ventricles, and, in any case, a want of complete co-ordination between the auricles and ventricles; in other words, there is a physiological irregularity of the heart.*

3. *With stronger vagus-excitation the auricles have either ceased to beat, or the impulses which pass from them to the ventricles are too weak to excite the latter to contraction, and the ventricles are left entirely to contract by their independent intrinsic mechanism, and are completely freed from the control of the vagus, save that this nerve has still some control over their excitability.*

It must be understood that the strength of the induced-current required to produce these successive stages varies in different animals, presumably also, therefore, in the same animal under different conditions. Before leaving the effects of direct excitation of the lower end of the cut vago-sympathetic, it must be stated that, in some exceptional cases, the force of the ventricular contractions appears from the curves obtained to be very materially weakened for a short time after the commencement of the stimulation. This *temporary* reduction in strength is due, in some cases, to certain parts

of the heart wall not contracting at each beat, and these partial contractions can be recognised by the unaided eye. In some cases, however, where the ventricular beat is evidently weakened by direct excitation of the vago-sympathetic, there is no visible evidence of partial contractions of the ventricular walls. We believe, nevertheless, that these cases must be ascribed to partial contraction, and are, therefore, inclined to class them with those first mentioned, in which it is possible to see, by the unaided eye, that the contractions do not take place in all the muscular bundles composing the ventricular wall. Of this, however, we can give no direct proof. We can only say that, in those rare cases where this unmistakable weakening shows itself, it lasts only for a short time after the commencement of the excitation of the nerve, and that, if the excitation be continued, the beats, which are usually irregular in force as well as weak, become rapidly stronger. In this respect the weakening follows the same course as the depression of excitability, and is, therefore, very probably due to it.

SECTION V.—THE EFFECTS OF DIRECT STIMULATION OF THE AUGMENTOR NERVES ON THE HEART. [Figs. 14–16.]

Before proceeding to consider the characteristics of reflex excitation of the vagus, and the part played by that nerve in the economy, it will simplify matters if we describe the effects of direct excitation of the other nerves which pass to the heart from the central nervous system. Of these the most readily and frequently called into play are the nervi accelerantes, or nervi augmentores, as they may more appropriately be called, which proceed to the heart mainly by the 2nd dorsal roots, through the ganglion stellatum, passing, usually, by both anterior and posterior segments of the annulus of VIEUSSENS to the inferior cervical ganglion, whence they reach the heart by the rami cardiaci, although sometimes, as GASKELL* has shown, some of the cardiac fibres in the annulus do not enter the lower cervical ganglion at all, but pass directly, in one or more small branches, from the annulus to the cardiac plexus. In this section we have to do only with direct stimulation of the augmentor nerves, and in most of our experiments on this subject we found it most satisfactory to apply the electrodes to one or both segments of the annulus, although, sometimes, we stimulated the cardiac branches which leave the inferior cervical ganglion.

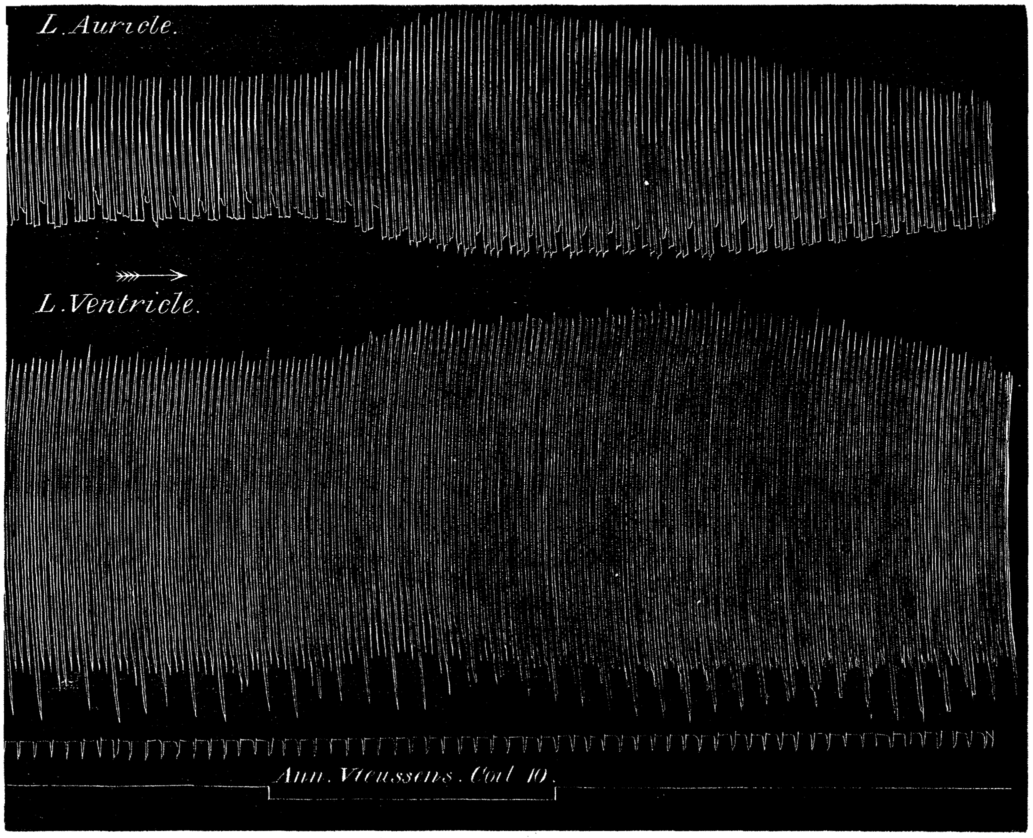
As we will presently show, there accompany the augmentors, in the paths we have referred to, certain other cardiac nerves which affect the organ in a different way from the nervi augmentores. When, however, these two kinds of fibres are called into action at the same time it is easy enough to distinguish their effects, and the curves of Figs. 14 and 15 may safely be taken as examples of pure augmentor action. They are both myocardiographic curves, with the auricular tracing above and the ventricular below. In both curves upward movement of the lever point corresponds to contraction of auricle and ventricle respectively.

* GASKELL, 'Journal of Physiology,' vol. 7, p. 1.

I. The Accelerant Effects of the Nervi Augmentores.

With regard, first of all, to the effect of augmentor excitation on the rate of beat of the heart. It can be seen that in the tracing in Fig. 14 the acceleration produced is very slight, viz., from 23 beats in 10 seconds, before the current was turned on,

Fig. 14.



Myocardiographic tracings [original size] from L. Auricle (above) and L. Ventricle (below). *Contraction, in both cases, caused upward movements of the lever points,* so that the upper margins of the tracings are the systolic, and the lower the diastolic. Stimulation of the cardiac end of the cut anterior segment of the L. annulus of Vieussens causes increased expansion and contraction of both auricle and ventricle. The acceleration is so slight as to be barely appreciable. The augmentor effects begin gradually and some seconds after the commencement of the excitation. They also diminish gradually, being still apparent a minute or two after the stimulation has ceased. The tracings show that the different effects of the excitation on the degree of expansion and contraction of the auricle, and the similar effects on the ventricle, do not go exactly hand-in-hand. The rate of beat is quickened from 23 beats in 10 secs. before to 24 in 10 secs. during the stimulation.

to 24 in the same space of time when the effect on the heart was most strongly marked. We have given this curve of augmentor action intentionally, to show how slight the accelerant action of the nerve fibres in question may be. In other cases, it need hardly be said, the acceleration produced may be very much more marked. The

acceleration depends, *cæteris paribus,* on the rate at which the heart is beating at the time when the nerve is excited. If that rate be slow, the acceleration is greater than it is with an initially quick-beating heart. The quicker the heart is beating to begin with, the less marked is the acceleration. According to our experience, whenever there is any effect at all produced by excitation of augmentor fibres, there is also some acceleration, but it may be even less than that shown in Fig. 14, and only discoverable on carefully measuring out the tracing. With relatively slow-beating hearts accelerations, as marked as those first observed by LUDWIG and his pupils are met with. To summarise: *the accelerating effect of the nervi augmentores is less when the heart is beating fast before the nerve is stimulated, so that, with a certain rapidity, which appears to vary with each animal, and the condition of the animal, strong and otherwise effective excitation of the augmentores produces so slight an acceleration of the heart that it is only to be discovered by measuring out the curve.*

Fig. 14 shows, also, what is sufficiently evident in most of our augmentor curves, viz., that the increase in force of the auricle and ventricle bears no proportion to the acceleration of the heart which may be produced by excitation of these nerve fibres. This, of itself, can, we imagine, bear but one interpretation, viz., that the acceleration and the augmentation in force of the heart's contractions are independent effects of the action of these nerve fibres, although perhaps it is safer to say that *if both acceleration and augmentation be produced by the same mechanism, e.g., by increasing the catabolic changes in the nerve-centres and the muscular fibres of the heart respectively, the results vary so much with the condition of the nervous and muscular tissues of the heart at the time of the excitation that the acceleration and the augmentation in force bear no apparent relation to one another in degree.* When we come to consider the inter-action of the vagi and augmentores it will be seen that the effect of these nerves on the rhythm of the heart can be sharply distinguished from their effects on the force of the auricular and ventricular contractions.

2. EFFECT OF THE AUGMENTOR NERVES ON THE FORCE OF THE HEART'S CONTRACTIONS.

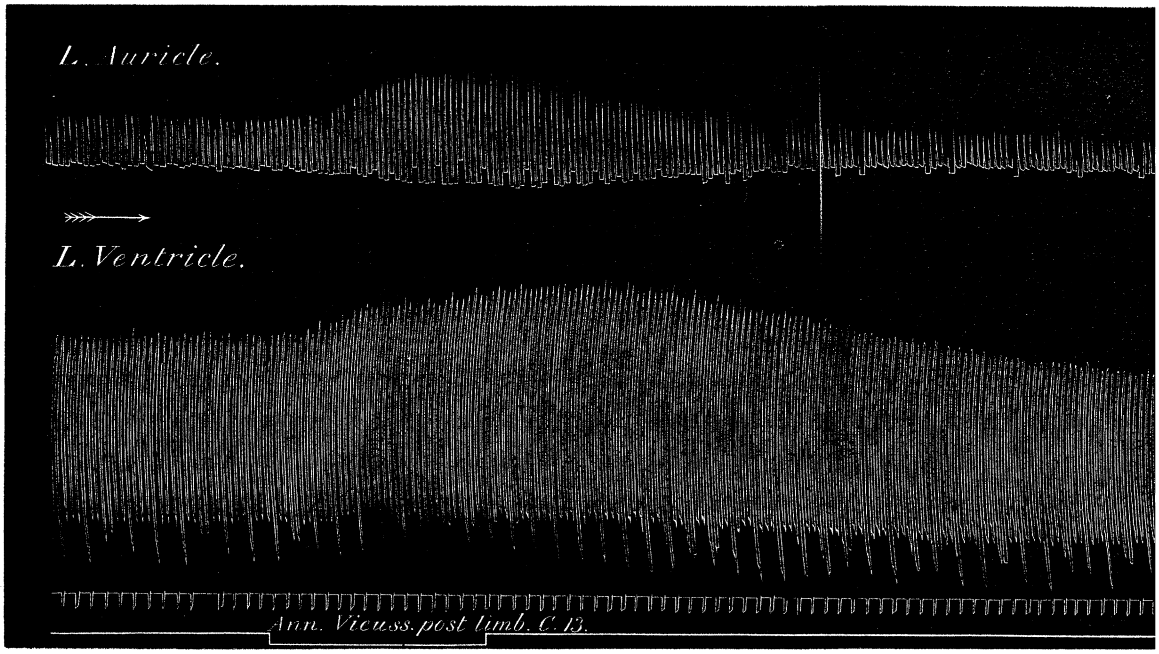
In the great majority of cases, excitation of the nervi augmentores produces marked increase of the force of contraction in both auricles and ventricles.

(*a.*) *On the Auricle in Diastole.*

As can be seen in Fig. 14, the auricle is affected in two distinct ways. In the first place, the expansion in diastole is increased. This is not due to any rise of pressure in the large veins, for, as will presently be pointed out, the venous pressure falls on direct excitation of the augmentor nerves. It is due to a primary change in the elasticity of the relaxed auricle, or, as some would prefer to call it, a lowering of

the tonus of the relaxed auricular wall. This change in the elasticity of the uncontracted auricular wall has no direct connection with the increase in force of the auricular contraction. They do not increase and diminish together, as is shown by the fact that the changes in the outline of the lower, or diastolic, margin of the curve, do not follow the same course as the changes in outline of the upper or systolic margin of the curve. This is even better shown in the auricular tracing of Fig. 15. In some cases, the change in the elasticity of the relaxed auricle which usually results from augmentor excitation is absent, or is so slightly marked as to be barely appreciable, while the increased force of the auricular contractions is very markedly

Fig. 15.



Myocardiographic tracings [two-thirds original size] from L. Auricle and Ventricle. Contraction as in Fig. 14. Stimulation of cardiac end of cut posterior segment of annulus of VIEUSSENS. The effects are somewhat similar to those seen in Fig. 14. The beat is quickened from 22·5 in 10 secs. before, to 24 during the stimulation.

present. It may be that in such cases the fall in the venous pressure, which results from augmentor action, by diminishing the distending force within the relaxed auricle, prevented the change in elasticity of the auricle from showing itself in the tracing; but, in many cases, such curves show that the relation in degree between these two effects of the augmentors on the auricle is not by any means a constant one. Like the increase in the force of the auricles and ventricles, the change in the elasticity of the relaxed auricular wall begins some 4 or 5 seconds or more after the commencement of the excitation, and increases gradually, while, on cessation of the excitation, the effect disappears slowly, sometimes many minutes elapsing before the

relaxed auricle has returned to the elasticity which it showed before the stimulation was commenced.

To summarise: *One of the effects of direct excitation of augmentor nerve fibres is to change the elasticity of the relaxed auricular wall, this change being independent in degree of the increase in the force of the auricular contractions, which also results from the excitation. It varies much in amount and is less constantly met with than the change in force.*

(*b.*) *On the Force of the Auricular Contractions.*

Although not invariably a marked effect of direct excitation of augmentor fibres, there is always some increase in the force of the auricular contractions, and, in the *vast majority* of cases, the increase in force of the auricular systole is a very prominent feature in the tracing. Figs. 14 and 15 are good average illustrations of this increase in the force of the auricular systole, which is well shown, also, in the examples of reflex excitation of the augmentores shown in Figs. 24–29. *A constant effect, therefore, of both direct and reflex excitation of the augmentores is to increase the force of the auricular contractions.*

(*c.*) *On the Output of the Heart and on the Venous pressure.*

As the function of the auricular systole is to pass the blood in the veins on into the ventricle, we would naturally expect to find that, since the nervi augmentores can increase the force of these contractions, they would thereby increase the amount of blood entering the ventricles in a given time, increasing to the same extent the output of the heart. That they do this is well shown in the cardiometric curve, Fig. 16, in which is seen the effect on the organ of reflex excitation of the nervi augmentores. As in our other cardiometric tracings, upward movement of the lever point corresponds to contraction of the heart, so that the upper limit gives the volume of the organ at the end of systole, and the lower the maximum diastolic volume. This curve shows that, on stimulation of the central end of the sciatic, the contraction-volume and the output of the heart become increased, in this case, by over 20 per cent.

We have not made any experiments on the effect of direct excitation of the nervi augmentores on the output of the heart, but believe that it is the same as that of reflex excitation, for the following reasons: *First,* excitation of the cardiac end of cut augmentor fibres raises the blood pressure in the systemic arteries, which cannot well be due to anything other than increased output of the heart; *secondly,* C. J. MARTIN* finds that direct excitation of the accelerans lowers the pressure of the blood in both

* We have to thank Dr. C. J. MARTIN for having allowed us to make use of his unpublished observations on the action of the augmentores on the pressure of the blood in the systemic and pulmonary veins, whereby we have been saved the labour of making these experiments ourselves.

the systemic and pulmonary veins, which cannot easily be explained otherwise than by increased flow from the veins into the ventricles.

Although, therefore, we have made no direct observations upon the subject, we conclude that *direct excitation of the augmentor fibres increases the output of the heart by increasing the force of the auricular contractions, causing, at the same time, a rise of blood pressure in the pulmonary and systemic arteries, and a fall of pressure in the systemic and pulmonary veins.*

Fig. 16.

Cardiometer curve [two-thirds original size.] The upper limit of this tracing represents the condition of the organ in systole. The tracing shows the TRAUBE-HERING (S. MAYER) curves. Effect of reflex excitation of the augmentores. [During the excitation the heart is dilated both in diastole and in systole, the increased expansion in the former being greater than in the latter, the contraction-volume being increased by about 20 per cent. at the point of maximum effect. As there is no change in the rate of beat of the heart the output is increased to the same extent as the contraction-volume.]

(*d.*) *On the Action of the Nervi Augmentores upon the Ventricles.*

1. *On the Diastolic Expansion of the Ventricles.*

We would naturally expect that the increased force of the auricular contractions would cause the ventricles to become more expanded in diastole; and such increased expansion, corresponding in time and degree to the increase in force of the auricular systole, can usually be recognised without difficulty in those of our curves which show the effect of direct stimulation of the augmentores affecting both auricles and ventricles. For examples of this we may refer to Figs. 14 and 15. Our curves

have never given us any reason for supposing that this increased expansion of the ventricles in diastole is other than passive in nature. There is no evidence that the tonus of the relaxed ventricle is affected in the same way as that of the relaxed auricle by augmentor stimulation. We conclude, therefore, that *the increased expansion of the ventricles in diastole which results from excitation of the augmentores is passive in nature, and due exclusively to the increased intra-ventricular pressure at the end of diastole, resulting from the increased force of the auricular contractions.*

2. *The Force of the Ventricular Contractions.*

In all our experiments on this subject we found that the ventricles contract more completely in systole as the result of direct excitation of the augmentores. As we have pointed out, direct stimulation of these nerves causes a rise of pressure in the pulmonary and systemic arteries, and therefore of the intra-ventricular pressure during systole, so that the force of the ventricular contractions must be increased. In curves 14 and 15 it can be seen that the increase in force of the ventricular contractions does not go hand in hand with the increase in force of the auricular contractions. This cannot be fully explained by the fact that changes in the arterial blood-pressure will apparently affect the one without affecting the other, and an examination of our curves rather points to the conclusion that the degree and duration of the increase in force which is produced by augmentor action on the auricles and ventricles respectively, varies with the condition of each of these parts at the time they are excited. We conclude, then, that *direct excitation of the nervi augmentores increases the force of the ventricular contractions, so that they contract more completely, diminishing the amount of residual blood, in spite of the fact that the arterial pressure is raised at the same time.*

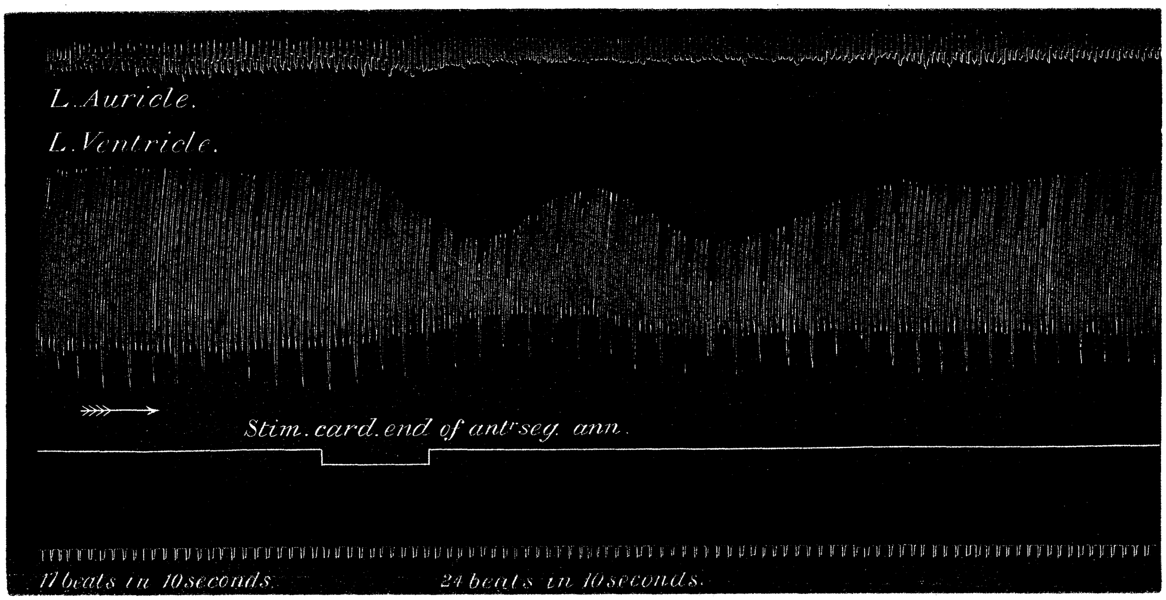
It will be seen, when we come to speak of the effect of reflex excitation of the augmentores, that this latter differs in some important particulars from that of direct stimulation. The tracings of Figs. 14, 15, and 16 show that great changes in the force of the heart's contractions may take place with little or no accompanying change in the rate of beat. It is important to keep this in mind, as also that the output of the heart may be doubled or trebled without any change of the rhythm.

SECTION VI.—CENTRIFUGAL NERVES OTHER THAN THE VAGI AND AUGMENTORES WHICH AFFECT THE HEART.

In our experiments upon the Mammalian heart, we have, again and again, obtained evidence that there are, running along the vago-sympathetics, and also passing to the heart by the annulus of VIEUSSENS, fibres which affect the heart in a manner which is unmistakably different from the effect on it of the vagi and augmentores. It was only by chance, so to speak, that we were at first able to isolate the action of these nerves. We have, so far, succeeded in isolating only one of them anatomically

—and in some respects, therefore, our observations on them are incomplete. Our reason for publishing our results in their present incomplete condition is that we hope that others will be led to take up a matter which we cannot for the present pursue further ourselves.

Fig. 17.



Myocardiographic tracings [two-thirds original size] from L. Auricle and Ventricle. (In this and the following curves, unless otherwise indicated, contraction causes upward movement of the lever point.) Effect of stimulation of the cardiac end of the cut anterior segments of the annulus of VIEUSSENS.

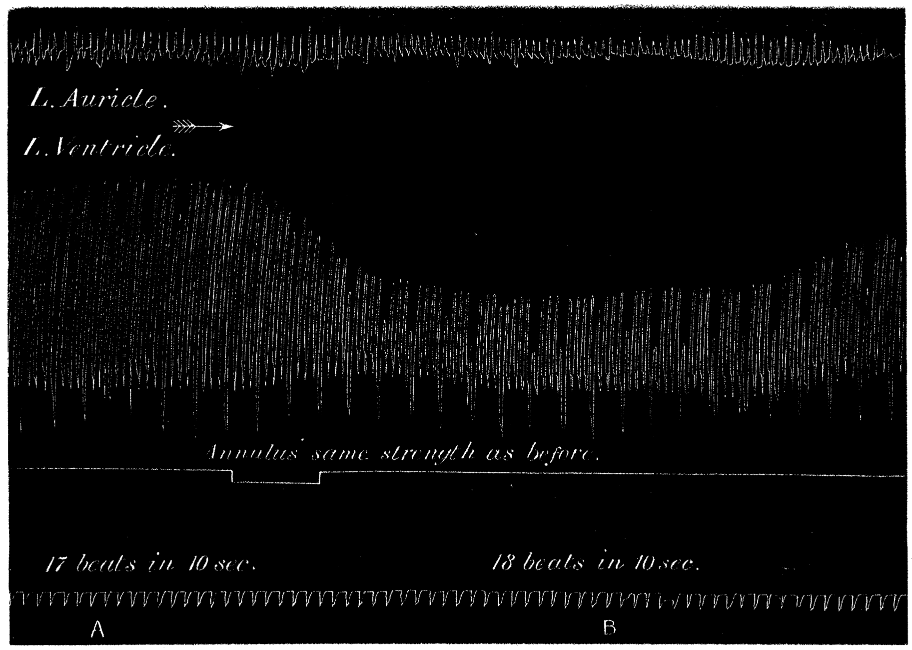
[The auricular tracing shows little change in the force of the beats of that part of the heart, the contractions of which had since the beginning of the experiment become, from some unknown cause, weaker and weaker.

The ventricular tracing shows marked weakening of the contractions with diminished expansion in diastole during the first part of the period of excitation, this primary weakening being accompanied by acceleration from 17·5 beats in 10 secs. before, to 20 in the same time, during the first period of weakening. Following the primary weakening is a period of increased force of contraction with a slight increase in the degree of diastolic expansion, shewing itself a little later than the increase in force of the contractions. During this second stage the rhythm is still further accelerated, viz., to 23 beats in 10 secs. Following this stage there is a period of weakening, after which the beats return to the force and frequence which they showed before the nerve was excited. It is to be noted that the excitation lasted only a short time, and had ceased before the second stage, that, namely, of increased force, showed itself on the tracing.]

In Figs. 17 and 18 (in which the movement upwards of the lever point corresponds to contraction of the auricles and ventricles), we show myocardiographic curves from the left auricle and ventricle of a Dog which had received a dose of atropin sufficient to completely paralyse the vagus, as we had assured ourselves by applying strong induction currents to both vago-sympathetic trunks. Fig. 17 shows the effect of excitation of the cardiac end of the cut anterior segment of the annulus of VIEUSSENS

(left side), the other segment having also been cut. It can be seen that the excitation caused, at first, a diminution in the force of the ventricular contractions, in the course of which, however, there is a well-defined increase in force lasting for a short time, and not sufficient to bring the contractions back to the force shown before application of the stimulus. We have evidently here a double effect; in the first place, a lowering of the force of the contractions, beginning soon after the stimulus

Fig. 18.



Myocardiographic tracings [two-thirds original size] from L. Auricle and Ventricle of same animal taken a few minutes later, the chief augmentor branch from the inferior cervical ganglion having been cut in the interval. Effects of stimulation of cardiac end of the cut anterior segment of the annulus, with the same strength of current as in Fig. 17. [The auricular beats are still weak, but the weakening effect on them of the excitation is better marked than in Fig. 17. The ventricular tracing shows well-marked weakening as a result of the excitation, but there is no appreciable augmentor effect superposed on the weakening as was the case before the augmentor branch was cut. Probably all the augmentor fibres were not severed, as there is a slight acceleration, from 17 beats in 10 secs., to 18 in the same time, and on careful inspection a slight rise of the upper limit can be seen to be present, which points also to the existence of a few uncut augmentor fibres. Those nerve fibres, therefore, which on excitation cause a weakening of the auricular and ventricular beats have apparently no influence on the rate of heart-beat.]

was applied, and lasting for some time after the excitation had ceased, on which are superposed augmentor effects, characterised by beginning late after the application of the stimulus, by being accompanied by acceleration (17 beats in 10 seconds before to 24·5 beats in 10 seconds during the maximum augmentor effect), and, thirdly, by a relative increase in the force of the ventricular contractions. Now it so happened in this case, that, on the left side, the chief augmentor fibres passed to the heart from

the inferior cervical ganglion by a single branch, stimulation of which in continuity caused typical augmentor action, as described in Section V. We now cut the branch, and again stimulated the annulus as before. The effect is shown in Fig. 18, where it can be seen that section of this branch has eliminated from the tracing the augmentor effect which showed itself so unmistakably in tracing 17, without affecting the action of those fibres which caused weakening of the ventricular and, to a less degree, of the auricular contractions. We have, in one or two other cases, obtained evidence, as clear as that recorded above, of the existence in the annulus of fibres which directly weaken the force of the contractions of both auricles and ventricles. These nerves are best sought for in the branches which in some Dogs pass directly from the stellate ganglion, or annulus, to the heart.

Of the existence of such fibres there is, then, no room for doubt. To summarise: *There pass from the stellate ganglion nerve fibres, other than the augmentors, which proceed to the heart, and which, on excitation, cause, or may cause marked weakening in the force of the ventricular and auricular contractions, whose action on the heart is, therefore, quite different from that of the vagi or augmentors.*

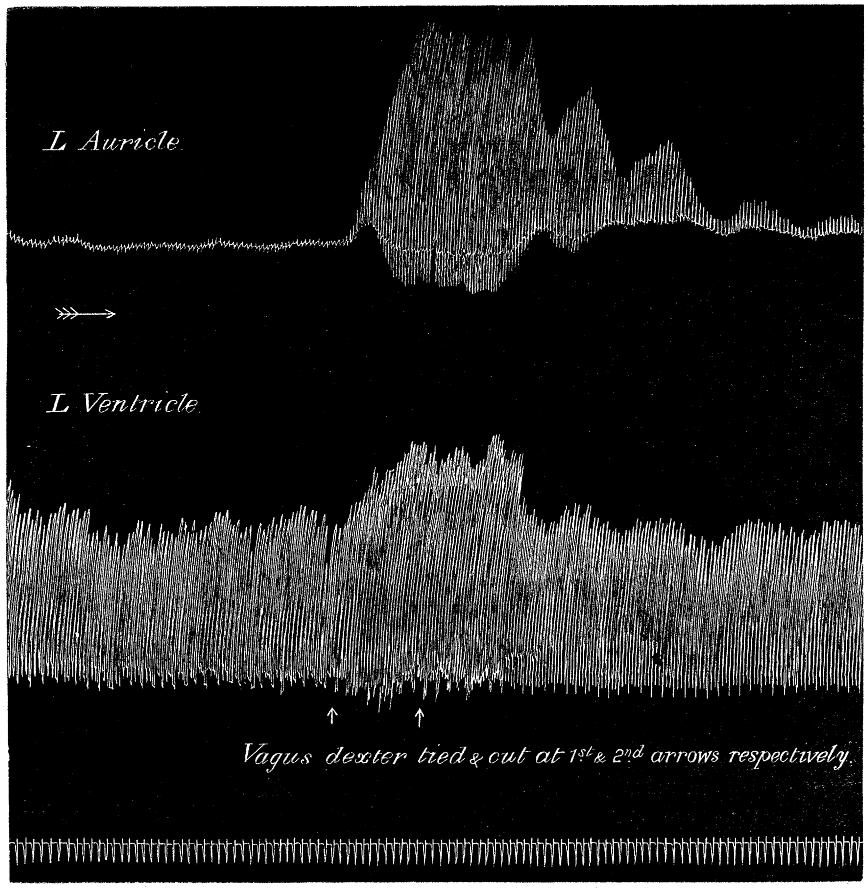
Why, it may be asked, if, on excitation these nerves produce an effect on the heart *before* the nervi augmentores do, and if their effect lasts longer than that of the augmentors, do we not *always* find evidences of their existence on stimulation of the lower cut ends of the annulus of VIEUSSENS? The answer to this is, that they by no means always pass by the annulus, which, so far as we know, is invariably the case with the greater part of the augmentor fibres. When they proceed to the heart by the small branch or branches which pass from the ganglion stellatum or the annulus, it is not usually possible even then to convince oneself that they are not intermixed with augmentor fibres, for the weakening and slowing, which they produce as a primary effect, may be followed by very strong after-effect of the opposite kind, viz., by increased force and frequence, which might be due to the presence of augmentor fibres, or might be a normal sequence of the primary effect of the nerve fibres in question. It is well worth while for some one to inquire further into the subject of these new cardiac nerves.

If we be asked what possible explanation could be given of the nature of the fibres in question, we can only say that they may *possibly* be vaso-constrictors for the coronary vessels, and that we have obtained evidence by direct experiment that the force of the heart's contractions is immediately increased or diminished by changes in the amount of blood flowing through the coronary vessels. We have, however, no direct proof that the nerve fibres in question are vaso-constrictors for the heart, and what we have given is only a *possible* explanation of their nature and mode of affecting the organ.

B.—Nerve Fibres Passing by the Vago-Sympathetics.

In the vast majority of cases stimulation of the lower cut end of one of the vago-sympathetics produces the effects already described in Section 4. There are,

Fig. 19.



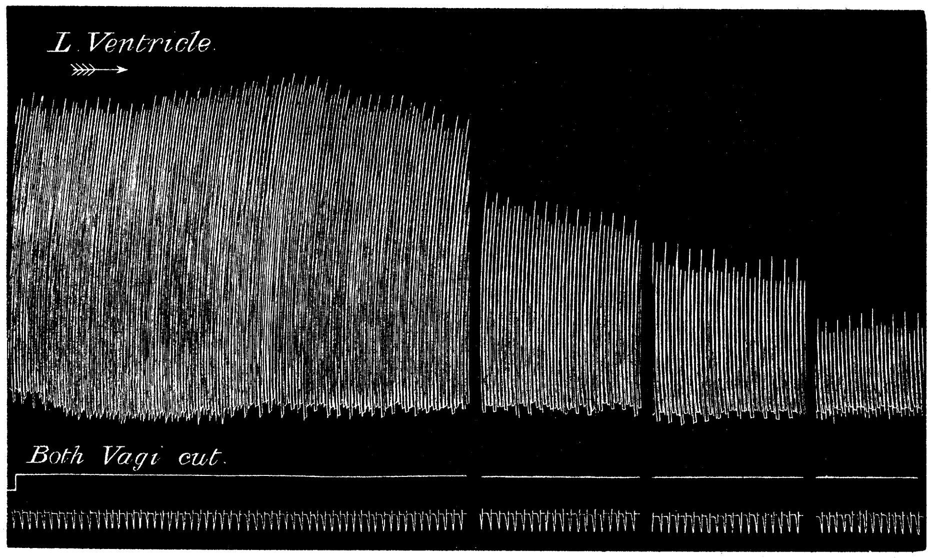
Myocardiographic tracings [original size] from L. Auricle and Ventricle. The auricles had ceased to beat from accidental irritation [of unknown nature] of the vagus centre in the heart. On mechanical irritation of the L. vago-sympathetic by tying and cutting—the nerve of the right side having been previously cut—the auricles temporarily recommenced to beat, and the force and frequence of the ventricles underwent temporary increase. The auricular contractions showed at one point rhythmic variations in force, similar to those described by Fano in the auricle of the Tortoise, and which are not very uncommonly met with in the mammalian auricle. [The rate of beat of the ventricle is quickened from 19 beats in 10 secs. before the excitation to 26 in the same time during the period of maximum effect.

The rapid appearance of the increase in force of the ventricular beats on the application of the excitation, as well as their comparatively abrupt return to their previous strength, differ from what is met with on excitation of true augmentor fibres.]

however, cases in which evidence can be obtained of other effects. In cases, namely, when, for some cause or other, the vagus mechanism in the heart itself is powerfully

excited, so that the auricles are more or less completely arrested, stimulation, either mechanical or by weak induced currents, sometimes causes a very marked increase in the force both of ventricles and auricles, accompanied, in most cases, by acceleration of the rhythm of the heart. This is well shown in Fig. 19. It might be supposed that these effects were due to the presence in the vago-sympathetic of augmentor fibres, such as are contained in the vagus in the Frog. We do not believe this to be the explanation, for the following reasons:—First, we have never found any other evidence of the presence of augmentor fibres in the vago-sympathetics; secondly, the effects in question do not resemble those resulting from direct excitation of the augmentors, in that they appear and disappear too rapidly after the application of

Fig. 20.



Myocardiographic curve [original size] from the Left Ventricle, showing the effects, under certain conditions, of section of both vagi upon the strength of the heart beat. Upward movement of the lever-point corresponded with contraction. The first part of the curve shows temporary increase in force immediately succeeding upon ligature and section of the two vago-sympathetics. This was followed by rapid progressive weakening of the ventricular contractions. The second part of the figure was taken after an interval of 30 seconds, and the third and fourth after intervals of 1 minute. The animal died in 3 or 4 minutes after the last tracing was taken.

the excitation. For the same reason and also because they can be produced by mechanical stimuli, we may exclude "escape of current" affecting the augmentor fibres in the inferior cervical ganglion. We have only met with them in ill-conditioned animals where, on applying the myocardiograph to the heart, we found that the auricular beats had been more or less completely arrested, and where this arrest could not be removed, as in the case with reflex excitation of the vagus, by section of these nerves in the neck. Here, therefore, stimulation of the peripheral end of the cut vago-sympathetic can produce no vagus action on the heart, but makes it possible for the effects of other fibres contained in the same trunk to show themselves.

In these cases the effect of stimulation may be, as we have said, to cause a very marked increase in the force of contraction both of the auricle and the ventricle, which may or may not be accompanied by acceleration. In these cases, also, section of both vagi in the neck does not arrest the vagus action, but may have a markedly weakening effect on the ventricles, the beat diminishing rapidly in force, so that the animal may die in less than a quarter of an hour after the nerves have been cut. This is well shown in Fig. 20, the first part of which shows temporary increase of force of the contractions of the left ventricle on cutting both vago-sympathetics, this being followed by rapid progressive weakening of the contractions. The second part of the figure was taken 30 seconds after the first, and the third and fourth after intervals of 1 minute. The animal died 2–3 minutes after the last tracing was taken.

Now, do the facts stated above prove the existence in the vago-sympathetics of the fibres which on stimulation increase the force of the auricular and ventricular contractions? They do, of course, in the case of the ill-conditioned animals from which the curves 19 and 20 were taken, but, in the case of such animals, it must be kept in mind that the condition of the heart was found to be different from that usually met with, in that the vagus mechanism in the heart itself was in a condition of excitation. It is, at the same time, difficult to see how the effects just described can be explained by any excitation of vagus fibres alone, and we conclude, therefore, that *there is a certain amount of evidence pointing towards the existence in the vago-sympathetics of other centrifugal cardiac nerves besides the vagus fibres proper, which other fibres, upon excitation under certain conditions, cause a marked increase in the force of the contractions of the auricles and ventricles, and which on being cut may withdraw from the heart some influence essential to its continued vitality.*

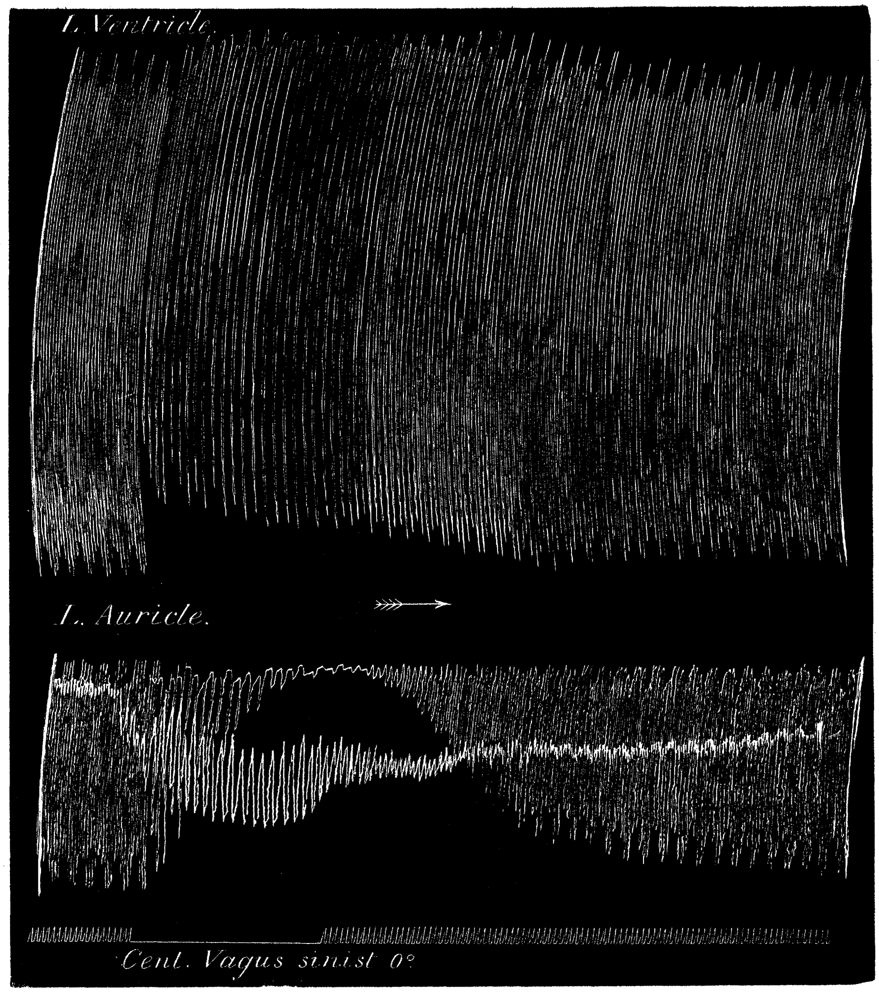
We have not succeeded in isolating anatomically the fibres to which we have just referred. We do not, therefore, know very much about them, and can only say that their characteristics could be well explained by the theory that they are vaso-dilators of the coronary system. In support of this possibility we have no direct evidence to offer.

SECTION VII.—ON REFLEX EXCITATION OF THE VAGUS.

Important as it is to know what is the effect of direct excitation of the vagus, it must be kept in mind that this manner of calling the nerve into activity is but a rough imitation of the natural mode in which the nerve is called into play, and that, moreover, the effects are liable to be obscured owing to other centrifugal nerve fibres being possibly excited at the same time. A much more satisfactory method of exciting the vagus is by reflex stimulation, as, in this case, the impulses which travel down the fibres are those generated by the vagus centre, and we have, therefore, a much more exact copy of the conditions under which the nerve is excited in the normal condition.

Stimulation of some sensory nerves excites both augmentors and vagi, and, to obtain with certainty pure vagus effects, the only centripetal fibres we know of are those contained in the vagi themselves. In Figs. 21, 22, and 23 we give typical

Fig. 21.

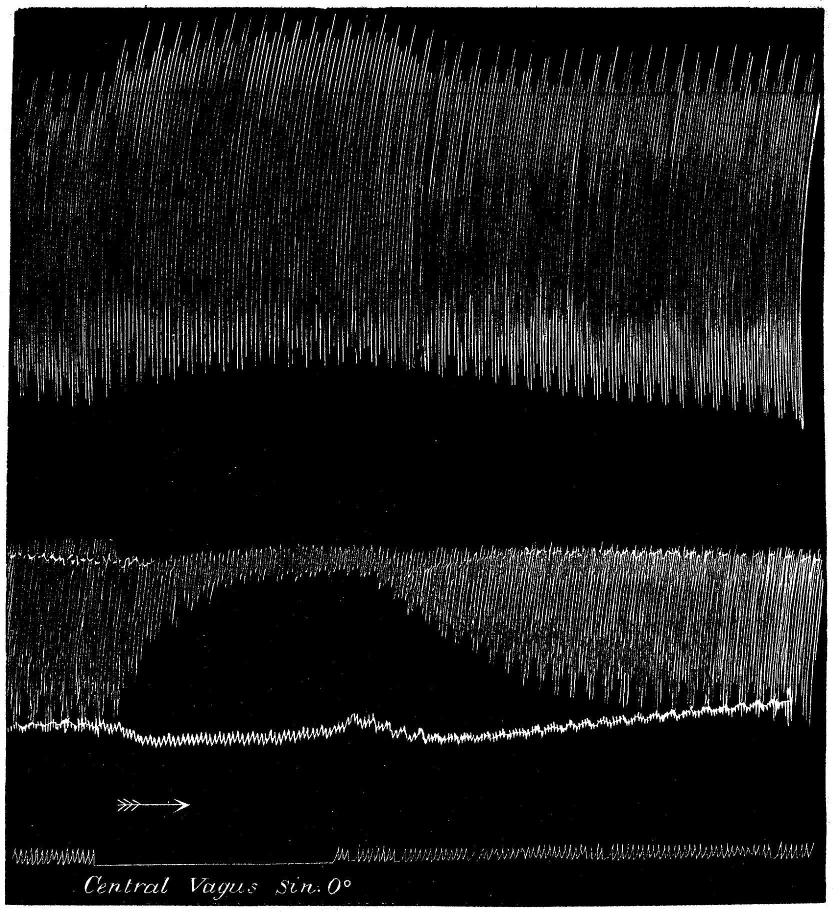


Myocardiographic tracings [original size] from Left Ventricle (above) and Left Ventricle (below), with simultaneous kymographic tracing. Contraction caused *downward* movement of the auricular and ventricular levers. The interruption of the time-curve shows the duration of the stimulus. Effect of excitation of the central end of the left vagus, the right vagus being intact. [In the ventricular tracing it can be seen that sudden slowing of the rhythm is accompanied by equally sudden increase in the diastolic expansion and diminution in the systolic contraction, as must necessarily be the case if the former be the cause of the two latter effects. In the case of the auricle, on the other hand, the diminution in the degree of contraction being the result of actual weakening of the contractions, and not an effect of the slowing, does not go hand-in-hand with the latter. The blood-pressure tracing from one of the carotids shows that, in this case, the diminished contraction of the ventricle is not due in any part to rise of the blood-pressure in the systemic arteries, but is due exclusively to the slowing, and takes place in spite of a slight fall in the intra-ventricular pressure.]

examples of vagus action resulting from moderate stimulation of the central end of one vago-sympathetic, the corresponding nerve of the other side being intact.

It can be seen that the effects upon the heart are pure vagus. In all three figures, the arterial blood-pressure is recorded at the same time as the myocardiographic curves from the left ventricle and auricle. In all three cases (from different animals),

Fig. 22.

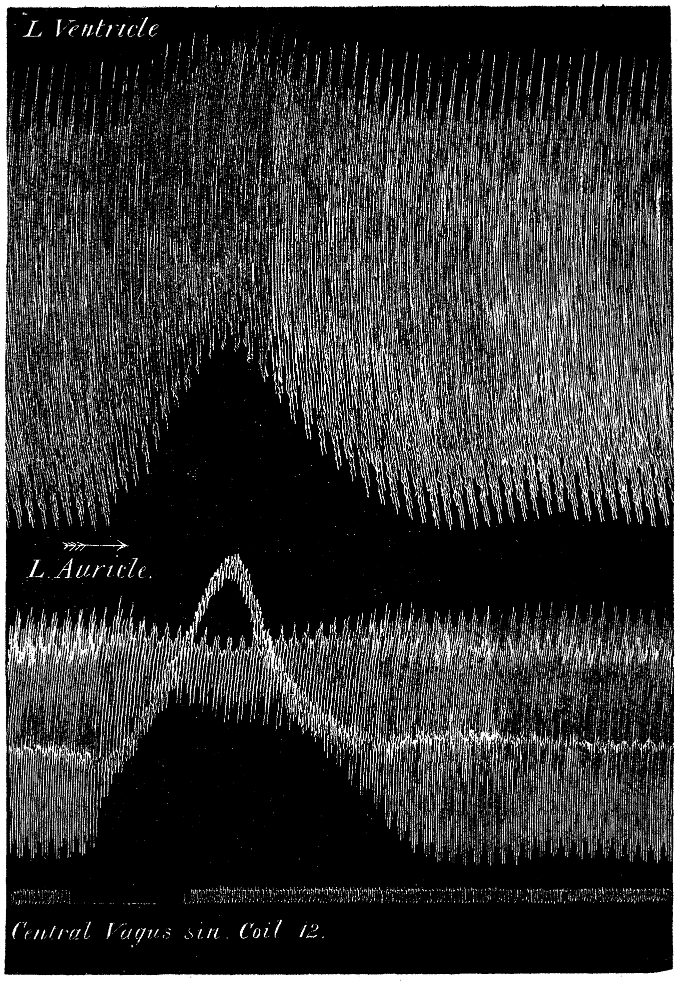


Myocardiographic tracings (original size) from Left Ventricle (above) and Left Auricle (below), with simultaneous blood-pressure tracing. As in Fig. 21, the period of stimulation is shown upon the time-curve. Effect of excitation of the central end of the left vagus, the nerve of the right side being intact. *Contraction*, as in Fig. 21, *causes downward movement.*

downward movement of the lever point is produced by contraction; and in all of the figures the auricular tracing is below. With regard to the auricular tracings, it can be seen that *the effects of reflex stimulation are the same as those of direct vagus excitation; there is the same weakening of the auricular contractions, which may go on to complete arrest.* In the case of the ventricles, the effects of reflex excitation differ from those obtained on direct stimulation, in so far that *there is never any evidence of weakening* of the contractions, which, as we have pointed out, is occasion-

ally met with as a result of direct excitation. In those cases where, as in Figs. 21 and 23, there is no rise of the blood-pressure in the systemic arteries, the rise of the lower margin of the ventricular tracing, indicating that the contraction has been less complete and that the ventricles contain more residual blood at the end of each systole, is never more than corresponds to the increased volume of blood which is

Fig. 23.



Myocardiographic tracings from Left Ventricle (above) and Auricle, with simultaneous record of blood-pressure. Here also *contraction causes downward movement* of the auricular and ventricular levers. The tracing shows the effects of stimulation of the central end of the left vagus, the right being intact. It can be seen that the diminished contraction of the ventricle follows the same curve as the blood-pressure tracing [the increase of the residual blood being, in part, due to the increased resistance to contraction, which results from the rise of the pressure in the systemic arteries.]

expelled at each contraction. In cases where the pressure of the blood in the systemic arteries rises as a result of stimulation of the central end of one of the vago-sympathetics, the increase in the amount of residual blood, as is well shown in Fig. 23, goes hand in hand with the rise of blood-pressure, that is to say, with

the increased resistance offered to the contractions of the left ventricle. As these figures show, reflex vagus excitation produces more satisfactory curves than can always be obtained by direct stimulation of the centrifugal fibres; they are more typical of the characters which we have described as the results of direct excitation of the nerve, and, with the above reservation, all that we have said as to the results of direct excitation applies also in the case of reflex stimulation. It is especially important to note that with reflex, as with direct, excitation, the same independent rhythm of the ventricle with the frequent irregularity of the heart readily shows itself. The same may be said with regard to the effect of reflex excitation of the vagus upon the output of the heart.

To summarise:—*The effects upon the heart of reflex excitation of the vagus are the same as those which we found resulting from direct excitation.*

SECTION VIII.—REFLEX EXCITATION OF THE NERVI AUGMENTORES.

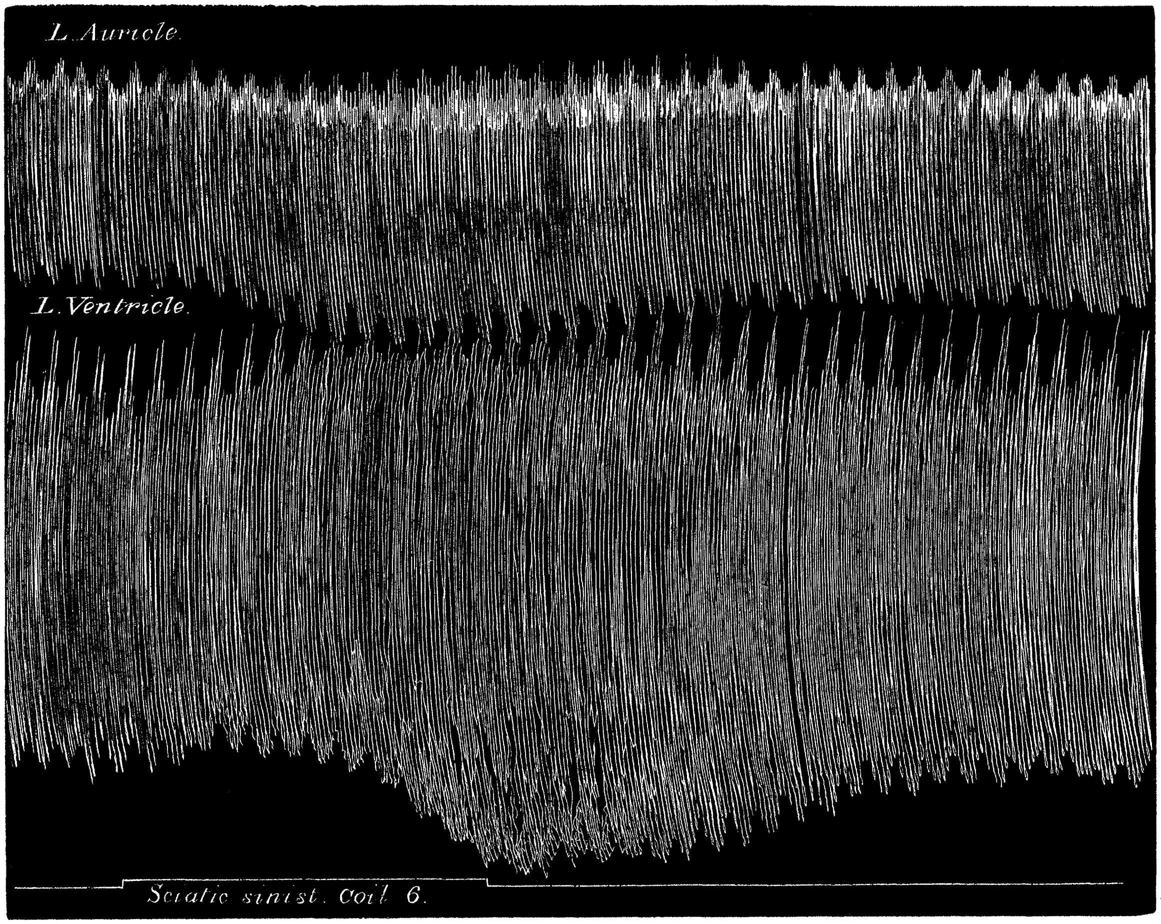
Upon stimulation of a mixed nerve like the sciatic, the first effect on the heart and, in most cases, the only effect on that organ, is to call into play typical augmentor action. In Figs. 24 and 25 are shown the effects which usually result from stimulation of the sciatic; these are both myocardiographic curves, with the auricular tracing above and the ventricular below, and, in both cases, contraction caused downward movement of the lever point. In both the increased strength of the auricular and ventricular contractions is well shown, as well as the other characteristics of augmentor action which we have described in Section V.

With regard, first of all, to acceleration, this is usually produced by excitation of the sciatic, but the degree of acceleration of the heart bears no proportion to the increase in strength of the contractions. In some cases, as is shown in the cardiometer curve, Fig. 16, no acceleration can be discovered upon measuring out the curve, although the increase in the contraction volume and output is well marked. We conclude then, that *reflex excitation of the augmentor fibres causes the same increases in force of the auricular and ventricular contractions as result from direct excitation of these nerves, and that there is usually, although not always, some acceleration recognisable upon measuring out the tracing.*

As can be seen from the curves, reflex augmentor action does not affect the force of the auricular and ventricular contractions respectively to the same degree, in this respect resembling direct excitation. As we have pointed out, and as is well shown in Fig. 16, the output of the heart is increased by reflex as well as by direct augmentor excitation. In Fig. 25 the blood-pressure was taken simultaneously with the myocardiographic records, and it shows the usual rise of pressure produced by excitation of a sensory nerve; in spite, however, of the increased resistance to contraction thereby produced, the left ventricle is so much increased in force as a result of the stimulus, that it contracts more completely than before the nerve was excited, and

thus the residual blood in the ventricle at the end of systole is lessened. In this case, therefore, the increase in force of the ventricular contraction more than counterbalances the resistance offered to that contraction by the rise in pressure. But this is by no means always the case. By no means rarely, the increase in force of the

Fig. 24.

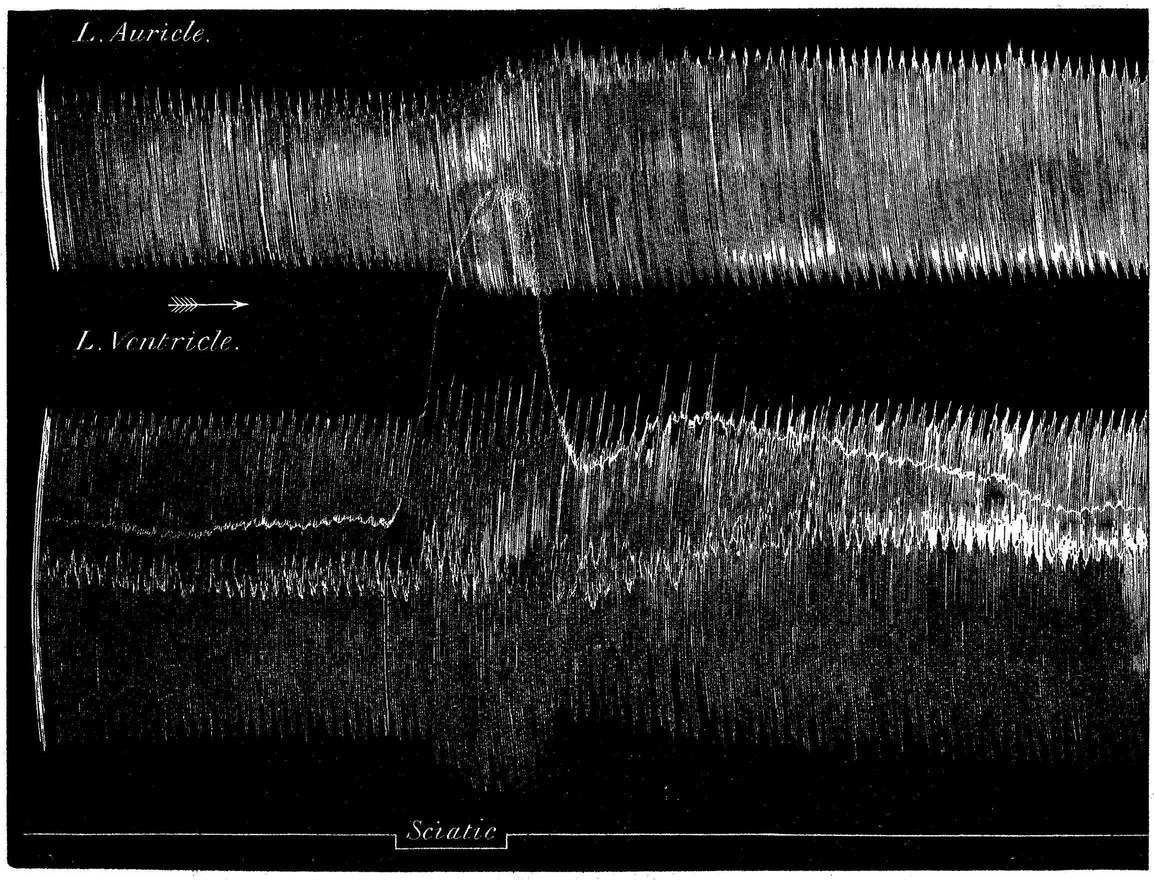


Myocardiographic tracings [original size] from L. Auricle and Ventricle. Contraction causing downward movement of the lever points. The curve shows effect of reflex excitation of the nervi augmentores, from the left sciatic nerve. [Like the others the curves read from left to right. The auricular tracing shows well-marked increase in force, but no increase in the diastolic expansion. The ventricular tracing shows equally well-marked increase in force, which does not go hand-in-hand with the strengthening of the auricular beats. The ventricle shows also increased expansion in diastole, which does go hand-in-hand with the increase in force of the auricular contractions.]

ventricle does not counterbalance the increased resistance to contraction, the result being that the ventricular systole is less complete, and the volume of residual blood therefore larger than before excitation was applied. This is well shown in Fig. 26, where it might seem, at first sight, as though the ventricle had actually been weakened by reflex augmentor action, did we not know how much the degree of

contraction of the ventricle is influenced by changes in the resistance offered by the blood-pressure to that contraction. It must be kept in mind, that the rise of pressure in the systemic vessels, which results from stimulation of a sensory nerve, is only in part due to the increased output of the heart, and that it would be a

Fig. 25.



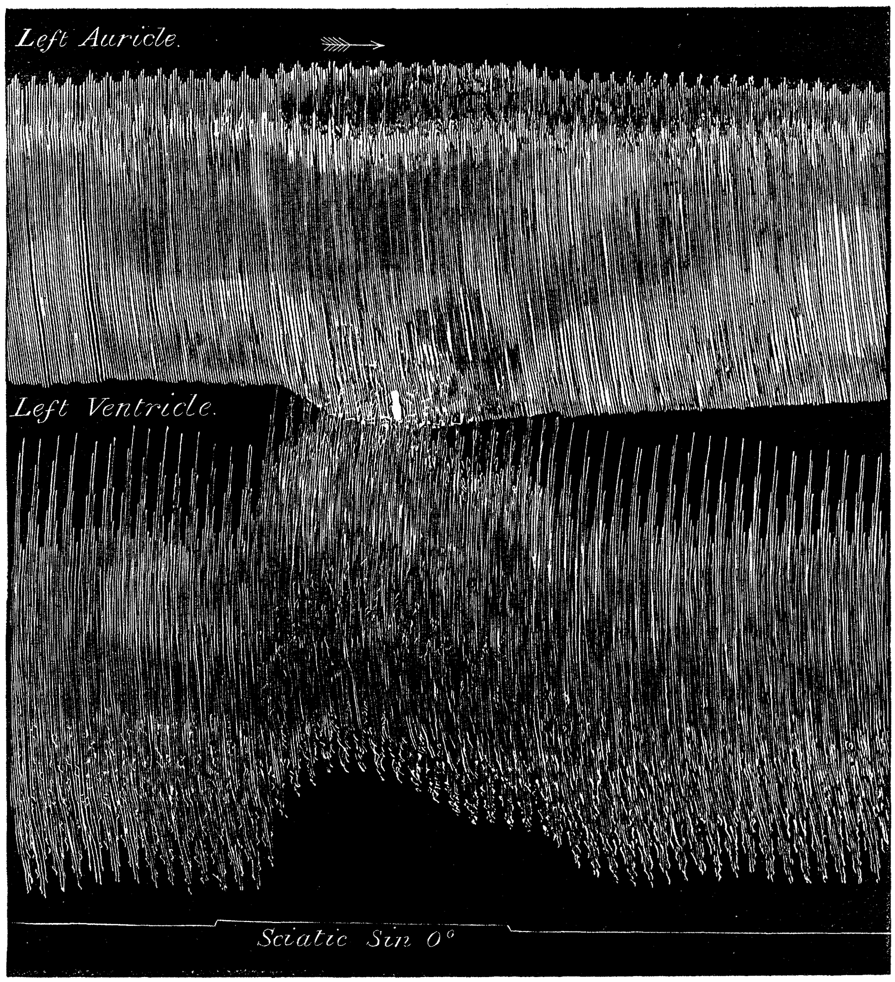
Myocardiographic tracings [original size] from L. Auricle and Ventricle. Contraction caused downward movement of the lever-points. There is a simultaneous blood-pressure record. The effect of reflex excitation of the nervi augmentores from the sciatic nerve. [The auricular tracing shows increased force of contraction in systole, and increased expansion in diastole, but these two effects do not go hand-in-hand. The ventricular beats are increased in force, and the contractions are more complete in spite of the increased resistance to contraction which results from the considerable rise of blood-pressure in the sytemic arteries. Probably a part of the increase in force of the ventricles is due to the flushing of the coronary vessels with blood, seeing that the former agrees so closely with the rise in the aortic pressure.]

wonderful thing did the degree of increased force of the ventricular contractions correspond exactly to the increased resistance which is largely due to contraction of the vessels of certain vascular areas.

We conclude then that, *although there always is an increase in force of the*

ventricular contractions as a result of stimulation of certain sensory nerves, yet that this increase in force seldom, if ever, exactly counterbalances the increased resistance to contraction which results from rise of pressure in the systemic vessels, and that sometimes the increased force of contraction more than counterbalances the increased resistance, while in other cases the increase in force does not suffice to do so.

Fig. 26.



Myocardiographic curve [original size] from L. Auricle and Ventricle, contraction causing downward movement of the lever-points. Effects of excitation of the sciatic. The ventricle contracts less completely during the excitation owing to the rise of the blood-pressure preventing the increased force of the contractions showing themselves. The increase in force of the auricular contractions is well marked.

The importance of this want of accordance between the increase in the force of the left ventricle, and the increase in the work which it is called upon to do, can hardly, we think, be over-estimated, and in a future section we will make such comments upon it as appear to us of practical interest to the physiologist and the

physician; in the meantime we need only say that the physiological dilation of the left ventricle, which often enough shows itself in spite of augmentor action, is, in the hearts of healthy, well-fed animals, moderate in amount, and does not lead to any diminution of the output of the organ. In the case, however, of animals with weak hearts, this physiological dilation may assume excessive proportions, and may lead to failure of the auriculo-ventricular valves and diminution of the output of the heart, in other words, to heart-failure from inability to meet an increase of work which a healthy, well-fed heart can bear without difficulty.

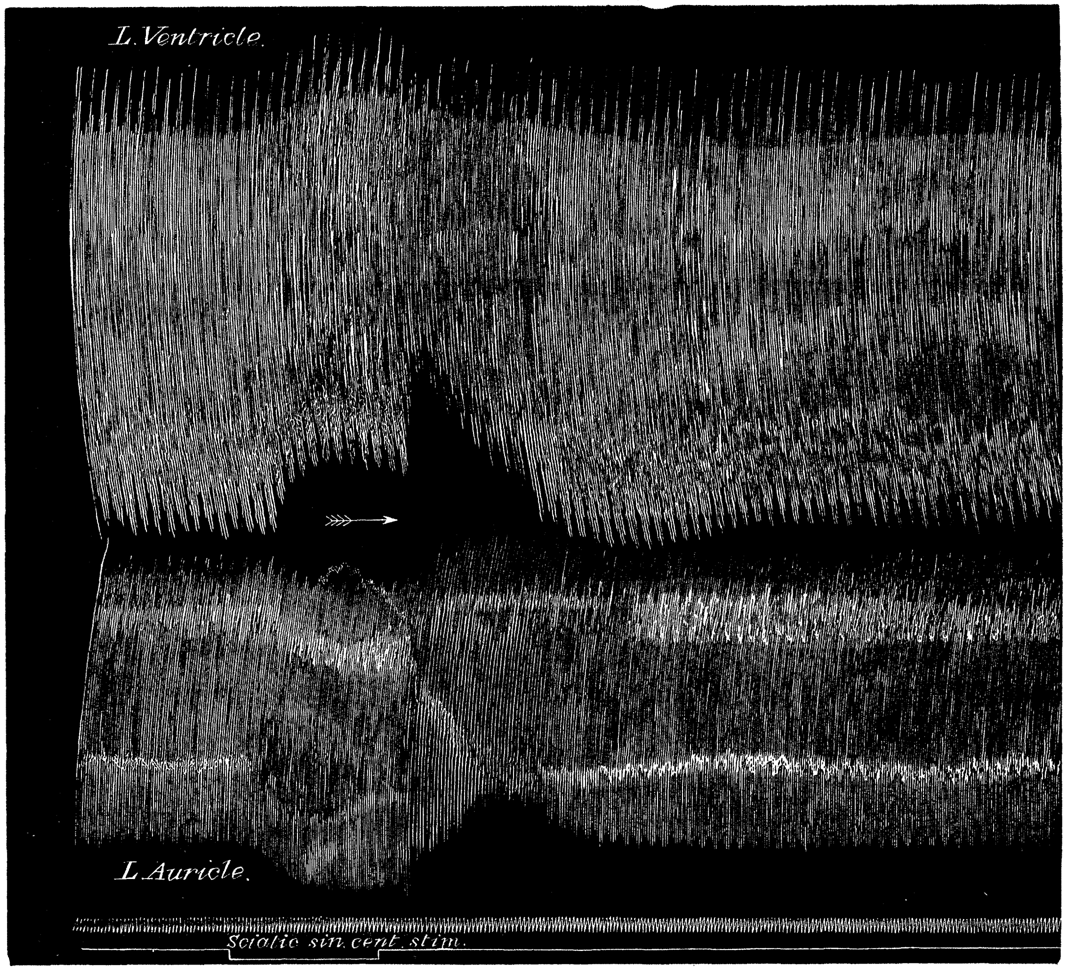
SECTION IX.—REFLEX EXCITATION OF BOTH AUGMENTORES AND VAGI.

In our last section we described the usual effect upon the heart of stimulating a sensory nerve. By no means rarely, however, stimulation of such a nerve as the sciatic produces a curious combination of augmentor and vagus effects upon the heart. It seems to us that this combination is met with more frequently upon stimulating the splanchnic (central cut end) than when such a nerve as the sciatic is excited. The combination of these reflexes upon stimulating a single nerve trunk is to us of extreme interest, throwing, as it does, considerable light on the relations to one another of the augmentores and vagi. In Figs. 27, 28, and 29 are given examples of stimulation of a sensory nerve calling into play both the augmentor and the vagus fibres. In all of these myocardiographic curves, the ventricular tracing is above and the auricular below, and, in all, downward movement of the lever point was produced by contraction. In all of them it can be seen that, during the stimulation, unmistakable augmentor effects are produced upon the heart; the auricular and ventricular contractions are increased in force, although this is hidden in the case of the ventricular tracing of Fig. 27, by the physiological dilation referred to at the end of last section. As soon, however, as the excitation came to an end, in all of them unmistakable vagus action showed itself, the transition from the augmentor to the vagus phase being abrupt, so much so that the point where one phase passes into the other may be exactly localised, the vagus effect becoming rapidly the more marked, and only gradually subsiding, leaving the heart, eventually, in the same condition as before the application of the stimulus. To summarise: *by no means infrequently excitation of a sensory nerve produces well-marked augmentor effects upon the heart, which, on the stimulus ceasing, are abruptly replaced by equally well-marked vagus effects.*

Did we depend upon these curves alone—those, that is, represented in Figs. 27, 28, and 29—it would be difficult to avoid the conclusion that stimulation of a sensory nerve excites only the augmentor centre, and that the vagus action is an indirect and secondary effect, due, possibly, to the rise of blood-pressure. We have, however, a certain number of curves which show that before the cessation of the stimulation, vagus action may replace the augmentor effect which most usually results from excitation of

a sensory nerve, and we have one or two examples of vagus effect alone resulting from such stimulation. An example of the former is given in Fig. 30, in which, during

Fig. 27.



Myocardiographic tracings [original size] from L. Ventricle (above) and L. Auricle, contraction causing downward movement of the lever point. There is a simultaneous record of the blood-pressure. During the stimulation of the sciatic nerve there are typical augmentor effects. After stimulation these are followed by typical vagus actions. [During the excitation the beats of the heart are increased in frequence (from 15 in 10 secs. before, to 20 in the same time while the stimulation lasts) as well as in force. The latter effect only shows itself in the auricular tracing, the ventricular contractions being less complete, owing to the rise of the systemic arterial blood-pressure. The increased resistance to the contraction of the left ventricle due to the rise of blood-pressure, more than counter-balances, in this case, the increase in the force of the contractions.

The secondary vagus effects show slowing of the rhythm to 10·5 beats in 10 secs., along with the other typical influences of this nerve on the characters of the auricular and ventricular contractions respectively.]

stimulation of the left splanchnic, the slight augmentor effect is replaced by unmistakable vagus action. We must therefore conclude that stimulation of the central end of the sciatic or splanchnic excites both the augmentor and vagus centres, but that

the excitation of the former centre is so much more powerful than that of the vagus centre, that the augmentor effect shows itself either alone or as the first result upon the heart of stimulation, and we must also assume that the degree of excitation of the augmentor centre becomes lessened earlier than that of the vagus centre, so that the vagus action replaces the augmentor action either when the stimulus ceases, or in some cases during the time that stimulation is being carried on; also, that in some very exceptional cases, the vagus effect alone may be the one to manifest itself.

It is important to note that this short duration of the state of excitation of the augmentor centre as compared with that of the vagus centre is the opposite of the well-recognised difference in duration of augmentor and vagus effects when each is called into play alone, by exciting *directly* the augmentor and vagus nerves respectively. The curves 27, 28, and 29, sufficiently show that the change in ratio in the degree of activity of the augmentor and vagus centres usually takes place abruptly, and as we know that reflex excitation of the vagus centre alone takes effect rapidly, we must assume that the supervention of the vagus in such curves as Figs. 27, 28, and 29 must be due, not to an increase of the vagus action when it first shows itself, but to a rapid diminution in the strength of the augmentor reflex. To summarise:—*Excitation of the sciatic or splanchnic causes impulses which travel to the augmentor and vagus centres, and tend to excite them both, but the augmentor is the more strongly excited of the two, so that augmentor effects alone most usually show themselves. The excitation of the vagus centre may either last longer or become relatively increased, as compared with that of the augmentor, so that vagus effects replace those of the* nervi augmentores. *In rare cases, excitation of the vagus centre may be stronger than that of the augmentor from the first.*

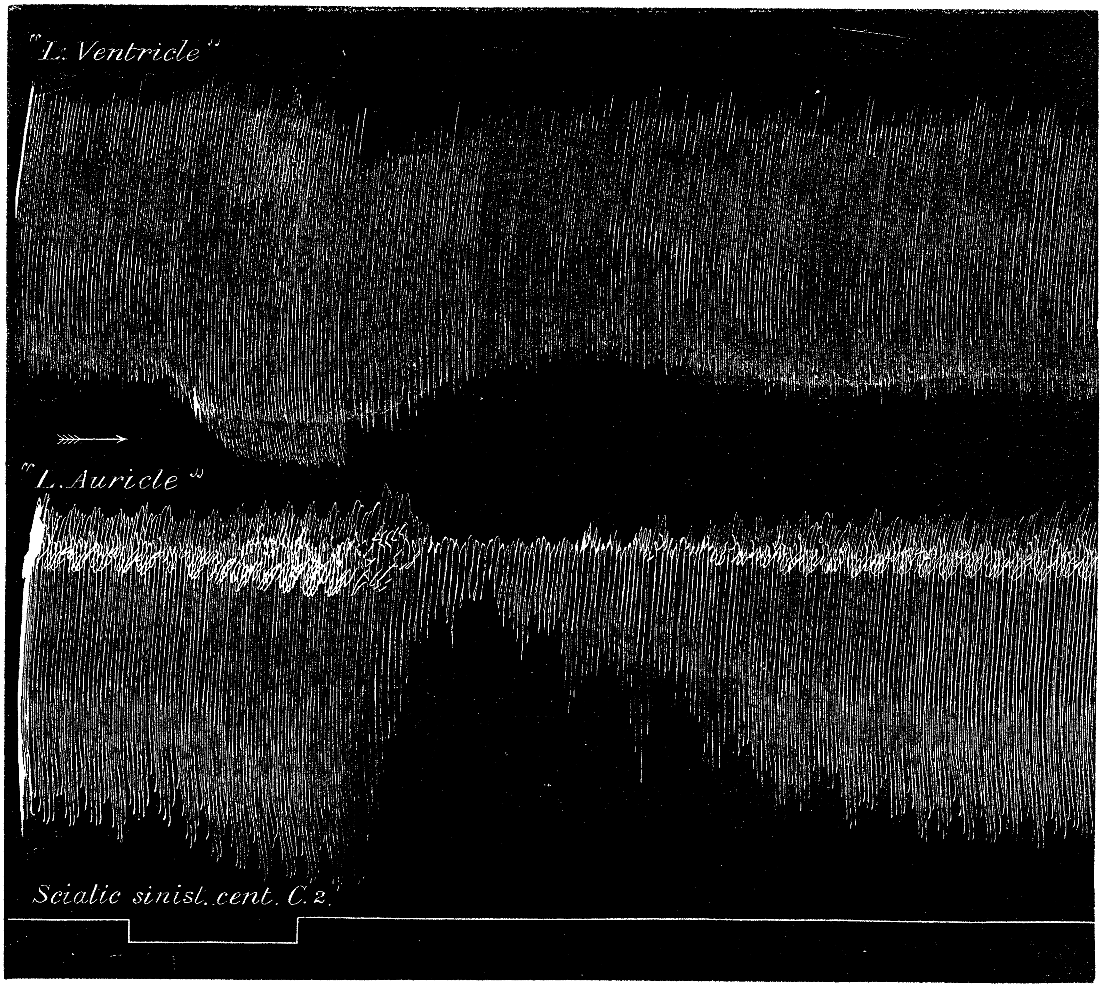
The curves, Figs. 27, 28, and 29, show that when the vagus action replaces the augmentor phase the strength of contraction of ventricle is affected as well as that of the auricle. A pure and simple augmentor effect on the force of contraction of the ventricles would disappear much more slowly than it does in the curves referred to. In the case of Fig. 27 the weakening of the ventricular systole is abrupt, and cannot be explained, as being only apparent, and due, really, to an increase in blood-pressure, as can be seen on comparing the kymographic tracing with that obtained from the ventricular wall. The weakening of the ventricular systole in curves 28 and 29 is less abrupt, but in them also the augmentor effect is unmistakably arrested.

Now, we have seen that vagus action of itself does not reduce the force of the ventricular contractions, but these curves conclusively show that when superposed on augmentor effects, the vagus does reduce the strength of contraction of the ventricles, and we must, therefore, conclude that, *although, in the absence of any augmentor action, the vagus does not reduce the force of ventricular systole, it does unmistakably have the power of inhibiting the strengthening influence which the augmentors exert upon the contractions of the ventricle.*

It cannot, therefore, be said without qualification, that the vagus is incapable of

reducing the force of the ventricular contractions. If the augmentor mechanism be in a condition of reflex excitation with the ventricles beating with any given degree of increase in force beyond that which they would otherwise present, the vagus nerve has the power of annihilating the augmentor influence upon the ventricle, and thereby reducing the force of its contractions to an extent corresponding with the increase in force of contraction which had resulted from the action of the nervi augmentores.

Fig. 28.



Myocardiographic tracings [original size] from L. Auricle and Ventricle (Ventricle above). Contraction of both causing downward movement of the lever points. During the excitation of the sciatic, reflex augmentor effects are well shown, and, upon cessation of the stimulus, are followed, as in Fig. 27, by equally well-marked vagus action. The auricles show at one point rhythmic changes in force.

In the vast majority of cases, when the reflex vagus influence follows on augmentor action the change shows itself simultaneously in both auricle and ventricle, but in rare cases this is not so.

In one of our experiments we found that the unmistakable augmentor effect upon

the ventricle, which was produced by excitation of one of the sciatics, lasted for some 12 to 14 seconds after it had been replaced in the auricle by vagus effects. It is interesting to note in this case that as soon as the augmentor effect upon the ventricle had been overcome by the vagus, the irregularity of the ventricular beats which this nerve can induce, showed itself.

We may therefore conclude that *the influence of the vagi and of the nervi augmentores may be combined together in the heart at one and the same time, so that the ventricles may show augmentor action, while the auricles show vagus effects.*

It is not impossible that the converse condition of the heart, with the auricles showing augmentor effect and the ventricles the influence of the vagus, may occasionally exist; but we have no tracings in which this can be recognised with certainty.

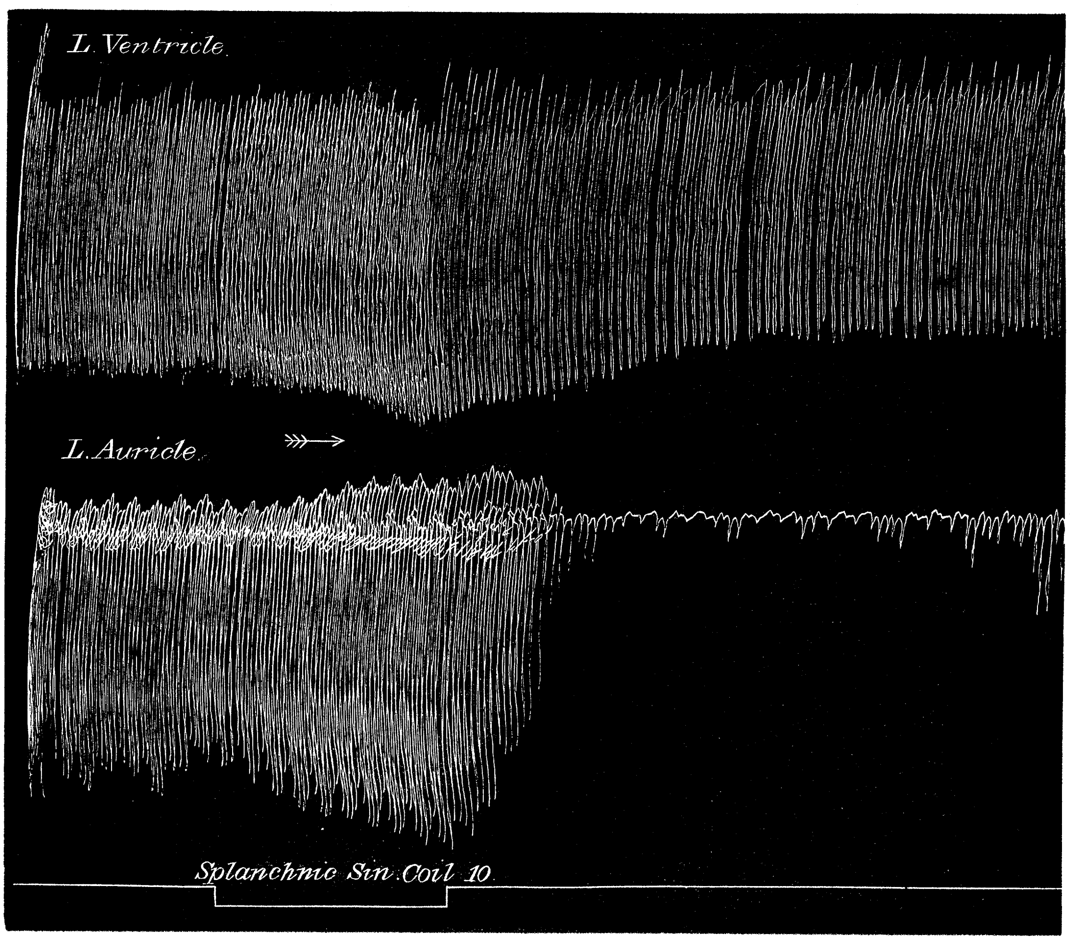
SECTION X.—ON THE PART PLAYED BY THE VAGUS MECHANISM IN THE ECONOMY.

As we have seen, the vagus not only slows the rate of heart-beat and increases the duration of the diastolic period as compared with the systole, but it also, by reducing the auricular contractions, diminishes the amount of blood entering the heart, an influence which is assisted by the elastic resistance to distension of the right ventricle in diastole limiting the amount of blood which can pass into it from the large veins. The more the heart is slowed, and the excitability of the ventricles reduced (without which great slowing would be impossible), the more will the input and output of the heart be lowered. The diminished inflow causes rise of pressure in the systemic and pulmonary veins, and fall of pressure in the corresponding arteries. This fall, and the diminution of the output, reduce the work done by the ventricles. Although the contraction volume is increased, this increase does not fully correspond to the slowing. The dilation of the ventricles which, as we have seen, is a constant accompaniment of vagus action, is, of itself, a source of economy to the heart, seeing that a greater part of the energy of the ventricular contraction is utilised in pumping out blood into the arteries, and less of it is wasted in distorting the heart-wall and in being transformed into heat. In other words, the useful work done at each contraction of the ventricles is increased without a corresponding increase in the catabolism of the ventricular muscle. As we have noted in Section III., the contractions of the ventricles would seem to gain in efficiency with increase, within certain limits, of their circumference, independently of the increased economy of the energy evolved at each contraction which we have just referred to. It must, of course, be *à priori* assumed that the increased height of the pulse-waves which results from vagus slowing is not beneficial to the circulation. In all of these particulars the heart is relieved of work by the action of the vagus, the circulation of course suffering to a certain extent. The mere fact that the centripetal fibres which call the vagus into play by reflex action come chiefly from the heart itself, shows that one part, and a very important

part, of the vagus function is to reduce the work done by the heart in the interest of the heart itself.

We conclude, then that *the vagus acts as a protecting nerve to the heart, reducing the work thrown upon that organ when, from fatigue or other causes, such relief is required by it.* The fact, however, that there exist centripetal fibres which call the vagus centre into activity, in such nerves as the sciatic and splanchnic, shows that the vagus mechanism may be called upon to act in the interests of other parts of the

Fig. 29.



Myocardiographic tracings [original size] of L. Ventricle and Auricle (below). The lever points move downwards with contraction. During the period of stimulation of the Left Splanchnic nerve there are well-marked augmentor effects present, followed, on cessation of the stimulus, by characteristic vagus action.

body whose circulation requires to be diminished. We conclude, therefore, that *the vagus may be used by other parts of the body to diminish the blood-pressure and the output of the heart, and thereby reduce the circulation.*

Amongst the organs whose protection against over-congestion is of the greatest importance, it need hardly be said that the central nervous system takes the foremost

place. It is well known that, if the intracranial pressure be raised artificially, powerful excitation of the vagus centre is produced. Vagus action also results from rise in the blood-pressure in the systemic arteries and the excitation thus produced can be shown to be due to the high pressure within the vessels of the central nervous system, and not to any direct effect of the rise of pressure on the heart. We must, therefore, look upon the vagus mechanism as a means by which the central nervous system gains protection against too great congestion.

The dependence on the blood-pressure of the degree of vagus action, and the readiness with which the vagus centre in the medulla is called into play by rise of the intracranial pressure, seem to us to indicate that the mechanism in question is especially employed in the interests of the central nervous system, as well as of the heart itself.

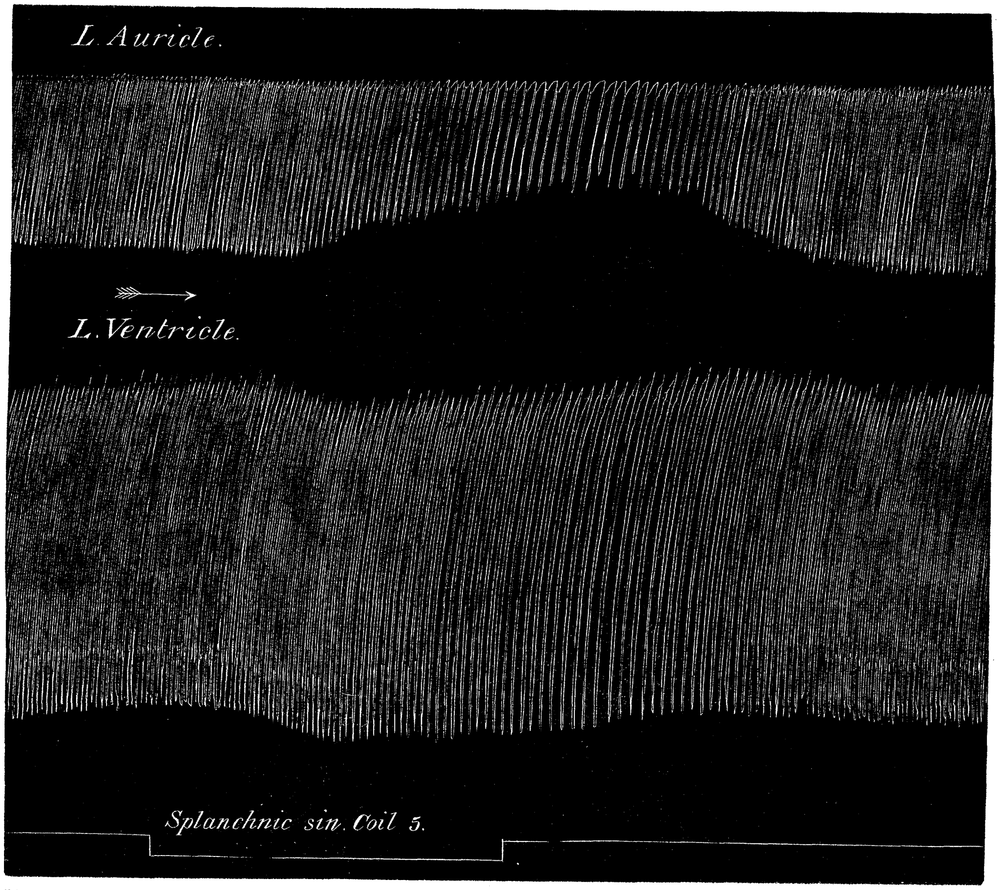
It is unnecessary for us to dwell upon the beautiful mechanism by which the vagus is prevented, no matter how strongly it be excited, from stopping the circulation altogether. The power of the vagi over the heart is limited. We have seen that their influence on the excitability of the ventricles is of short duration, and that, when excitation is carried beyond a certain point the nerve loses control over the action of the ventricles, except in so far that it prevents the increased force of contraction which the augmentor nerves are capable of producing. When carried beyond a certain point, therefore, vagus action takes off all control on the ventricles of the nerves by which the force and frequency of beat are normally regulated. To the physiologist this condition cannot but be of great interest; to the pathologist, the condition is one of extreme importance, seeing that it may safely be assumed that, wherever irregularity of the heart shows itself, the ventricles have been more or less completely deprived of the control exercised by both vagus and accelerans, so that the force and frequence of the contractions can no longer be regulated in complete accordance with the requirements of the heart itself, or of the other parts of the system. In other words, if the diseased or fatigued heart demand rest from the vagus centre very urgently, it may defeat its own object so far as the ventricles are concerned, seeing that in disease these latter may take on a rapid and irregular rhythm, with which the catabolism of the organ is much greater than corresponds with the amount of work done.

SECTION XI.—ON THE FUNCTION OF THE AUGMENTOR MECHANISM.

When we come to consider the place in the economy of the augmentors, the problem is simpler than in the case of the vagus. These nerves call upon the heart to increase its work and to send out more blood against a higher pressure. So far as we can learn, all those nervous influences (we exclude asphyxia) which lead to physiological excitation of the vaso-constrictor centres, thereby raising the blood-pressure in the systemic arteries, excite at the same time the augmentor centres in the cord.

For example, if spontaneous active movements supervene in the course of an experiment, the pressure is raised, the augmentor nerves being excited at the same time as certain of the vaso-constrictors. This excitation of the augmentor centre is frequently followed by vagus action, with slowing or irregularity of the ventricles. If, again, we stimulate the centripetal fibres contained in such a nerve as the sciatic or splanchnic, we get also augmentor effects on the heart, as well as the constriction of certain vessels, resulting from the action of certain vaso-motor nerves. The meaning of these facts appears to us simple enough, namely, that when the supply of blood to a part of the body is below what is required by its nutrition, it may be for the interest of

Fig. 30.



Myocardiographic tracings of Left Auricle and Ventricle; contraction causing downward movement of the lever points. During excitations of the central end of the left splanchnic nerve, there are at first (in the ventricular curve) slight indications of augmentor effects, soon replaced during the continuance of the excitation by unmistakable vagus effects.

the system as a whole, not only that the supply of certain other regions of the body, and especially of the digestive system, should temporarily be sacrificed, but also that the heart should, by the augmentor nerves, be made to contract more strongly, so that it is better able not only to overcome the increased resistance to its contraction, which results from the rise of blood-pressure, but that it should also, by increasing its

output, both raise the pressure still more and increase the quantity of blood which is available for the supply of the region which is in need of it.

Muscular exertion is, of course, one of the cases where the nervous system and the contracting muscles require an increased supply of blood, and where, therefore, it is evidently desirable in the interests of the economy that the augmentor fibres should temporarily increase the efficiency of the heart's action. We might give other examples of this connection between the system and the heart, and especially of the connection between the brain and the heart; we need, perhaps, only recall how readily the heart-beat is quickened and also strengthened by mental excitement.

A very important question remains to be considered, namely, how this sacrificing of the heart for the good of the rest of the system is limited, so that the economy does not suffer owing to failure of the heart from fatigue. Our curves in Figs. 27 to 30 show how readily and promptly the vagus mechanism steps in to limit the work thrown upon the organ; and it may be assumed that, in healthy normal conditions, the augmentor and vagus mechanism so act that the needs of the system are not allowed to injure the heart.

The function of the augmentors, in so far as the heart is concerned, appears to consist, in the first place, in increasing the amount of blood which is thrown into the ventricles by the more rapid and powerful contraction of the large veins and auricles; in this way the output of the heart is increased. In the second place, these nerves increase the force of the contractions of the two ventricles, so that they can perform the increased amount of work thrown upon them.

We conclude that the nervi augmentores cordis increase the output of the heart owing to the increased force of the auricular contractions, and that they are usually called into play in association with other mechanisms by which, owing to a rise of the pressure in the systemic veins, the input, and therefore the output, of the heart is still further increased; that the increased force of the ventricular contractions helps the heart to perform the increased work thrown upon it, not only from the increased output and the rise of arterial pressure which results therefrom, but also from the additional rise of pressure due to constriction of the arterioles of certain vascular areas. More work is, in this way, thrown upon the heart, which must be accompanied by increased catabolism of its substance; and it is therefore the function of the nervi augmentores to sacrifice the heart in order to increase the blood supply of other parts of the economy.

The interests of the heart are protected by the vagus mechanism, which readily becomes effective, reducing the work and tissue-waste of the heart, when the system no longer demands increased supply of blood, and also, presumably, when the heart, from fatigue, is no longer able to meet the demands made upon it.

SECTION XII.—COMPARISON OF THE ACTION OF THE VAGI AND AUGMENTORES UPON THE HEART, AND THEIR MODE OF INTERACTION.

We have seen that, in the case both of the vagi and the augmentores, the change in rate of the heart-beat has no close connection with the change in force of the

auricular or ventricular contractions. With the augmentores there may be very marked increase in force, without, in some cases, more than a very slight increase in rate, and with the vagus the weakening of the auricles, and, in some cases, of the ventricles, does not by any means correspond with the slowing. It is therefore desirable, in comparing the action of the augmentores and vagi on the heart, to distinguish the effects of these nerves on the rate of heart-beat, from their effects upon the force of the heart's contractions.

(*a.*) On the Rate of Heart-Beat.

Taking first of all the effects of the vagi and augmentores upon the rate of heart-beat, stimulation of the latter nerves causes a very slight acceleration of the rhythm, if the heart be already beating fairly fast. As need hardly be said, section of both vagi causes practically always a marked increase in the rate of beat, from which we must conclude that there are habitually passing down these nerves influences which restrain or slow the rhythmic centre in the sinus. If we now, by section of the vago-sympathetics, remove this restraining influence, what will be the effect, on the rate of beat, of excitation of the augmentores? If one of the vago-sympathetics be left intact, excitation of the augmentores, directly, or reflexly by a sensory nerve, causes quickening of the rhythm as well as increase in the force of the heart-beat. When, however, both vago-sympathetics have been cut, direct or reflex augmentor excitation produces no acceleration, as we have convinced ourselves by measuring out our curves with scrupulous accuracy. In more than a dozen satisfactory experiments we find that, after the vagi had been cut, excitation of the augmentores directly, or of the sciatic, splanchnic, &c., produced well-marked increase in force of the heart without *any* acceleration. On the other hand, as we have said, when one or both vagi are intact, augmentor excitation, direct or reflex, is always accompanied by acceleration of the heart, varying in degree with the rate of heart-beat at the time.

Since the augmentores only cause acceleration when the vagi are capable of slowing the heart, we must conclude that acceleration is caused through the medium of the latter nerves, and that the augmentores cause acceleration indirectly by removing the restraining influence of the vagi on the rhythmic centre or centres of the heart.

We conclude, then, that *the vagus governs the rate of heart-beat by restraining or inhibiting the rhythmic centre in the heart itself, and that the augmentores have no power to increase directly the activity of the rhythmic centre, but can only do so by cutting off the restraining effect of the vagus.*

(*b.*) On the Auricles.

When, on the other hand, we turn to the other influences of the nerves in question on the force of the heart's contraction, we must distinguish between their effects on the auricular and ventricular beats respectively. In the case of the auricles, after both

vagi have been cut, excitation of the augmentores causes a marked increase in the force of the auricular contractions; so much so, that there is little, if any, difference in the increase in force of the auricles from augmentor stimulation *after* section of both vago-sympathetics, as compared with that produced while these nerves are intact. The antagonism—if we may use the word provisionally—between the vagi and augmentores, as regards their effects on the force of the auricular contraction, differs, therefore, in at least one important particular from their antagonism as regards the rate of beat. In the one—namely, in the force of the contractions—if we cut off the heart from both vagi and augmentores, stimulation of the vagi alone reduces the contractile force, and stimulation of the other alone increases it; whereas, under similar conditions, the rate of beat of the heart is diminished by vagus action, but is not increased by excitation of the augmentores when, the vagi being paralysed, the former alone are stimulated.

This difference in the effects of these nerves, as to their action on the rate of beat and on the force of the heart's contractions respectively, to which we have had occasion to refer also when describing the influence of *direct* excitation of these nerves in question, is so unmistakable that it is difficult to believe that they are both called into play by the same sets of fibres in the vagi and augmentores respectively. We do not see that it is possible to avoid the conclusion that, in the case of the vagus, one set of fibres proceeds to the rhythmic centre, or centres, and that another set proceeds to the mechanism by which the force of the auricular contraction is regulated, be the latter nervous or contained in the muscular fibres themselves. In the case of the augmentores, we do not see that it is possible to avoid the conclusion that one set of fibres proceeds to the rhythmic centre of the heart, or to some part of the vagus above it—the inferior cervical ganglion?—where they have the power of cutting off the restraining influence of the vagus, while another set of fibres proceeds to the mechanism by which the force of the auricular contractions is affected.

The reasons for our conclusions are of a purely physiological kind, and are stated above; we have not sought to isolate anatomically these different fibres, if they exist as such. We cannot, however, but feel that it would be interesting to find what, in this connection, are the effects of stimulation of the different roots which enter the vagus, and also of the different sets of fibres converging to form the anterior roots of the second and certain other dorsal nerves.

(*c*.) On the Ventricles.

We have seen that the force of the ventricular systole is not diminished by vagus action unless the nervi augmentores be already in a condition of excitation, excepting in certain exceptional cases where, during the first part of vagus excitation, the contraction is apparently weakened owing to its not extending over the whole of the ventricular muscle. These latter exceptional cases we will deal with presently, and note here only that, in their respective effects upon the ventricle, the relation of

augmentor to vagus action differs in one important particular from that which as we have seen obtains in the case of the auricle. The one nerve (the vagus) has no direct effect on the force of the ventricular systole, unless this has been already strengthened by the action of the augmentores, while the other (the augmentor) has a distinct and marked strengthening effect after both vago-sympathetics have been cut through.

The parallelism of the interaction of these nerves, as regards the force of the ventricle to their interaction upon the rate of heart-beat, is too obvious to be overlooked. *In the case of the* rhythm, *the vagus directly affects the rate of beat, and the augmentores can only indirectly affect it by inhibiting the vagus, while the augmentores alone have the power of directly increasing the* force *of the ventricular systole, and the vagus can only act by inhibiting the augmentor influence.* It is true that the parallelism is not complete in so far that, while the vagi are habitually in activity restraining the rhythmic centre, the augmentores are only called into play when the system requires an increased supply of blood.

We see, then, that in the case of the rhythmic centre the vagus alone is capable of direct effect, the augmentores influencing it only indirectly through the vagus; in the case of the force of the auricular contraction both sets of nerves have direct influence, independently of one another; the force of the ventricular contraction, on the other hand, is directly affected by the augmentores only, and indirectly by the vagus through the augmentores.

SECTION XIII.—INFLUENCES OTHER THAN NERVOUS WHICH AFFECT THE FORCE OF THE HEART'S CONTRACTIONS, AND ITS OUTPUT.

(*a*.) THE BLOOD-PRESSURE IN THE SYSTEMIC ARTERIES.

If, having connected the right ventricle with a manometer (the one employed by us was that described by ROLLESTON*) of a kind fitted to record the maximum and minimum pressures within the cavity, the pulmonary artery be closed at its root for a few seconds, the maximum pressure within the ventricle is found to rise to a height which gives us some information as to the strength of the ventricular contractions. If, having found this in a given heart, we now close the aorta for a few seconds so as to raise greatly the pressure of the blood entering the coronary arteries, and thereby flush the heart wall, so to speak, with blood, and if we now repeat the temporary closure of the pulmonary artery, it is found that the pressure within the right ventricle is raised considerably higher than was the case before the temporary closure of the aorta. This experiment shows that the strength of the ventricular contractions is increased by increasing the pressure and flow of blood through the coronary arteries.

The converse experiment of lowering the pressure of blood in the coronaries can be most readily performed by removing a certain quantity of blood from the animal,

* ROLLESTON, "Observations on the Endocardial Pressure-curve;" 'Journal of Physiology,' vol. 8, 1887, p. 236.

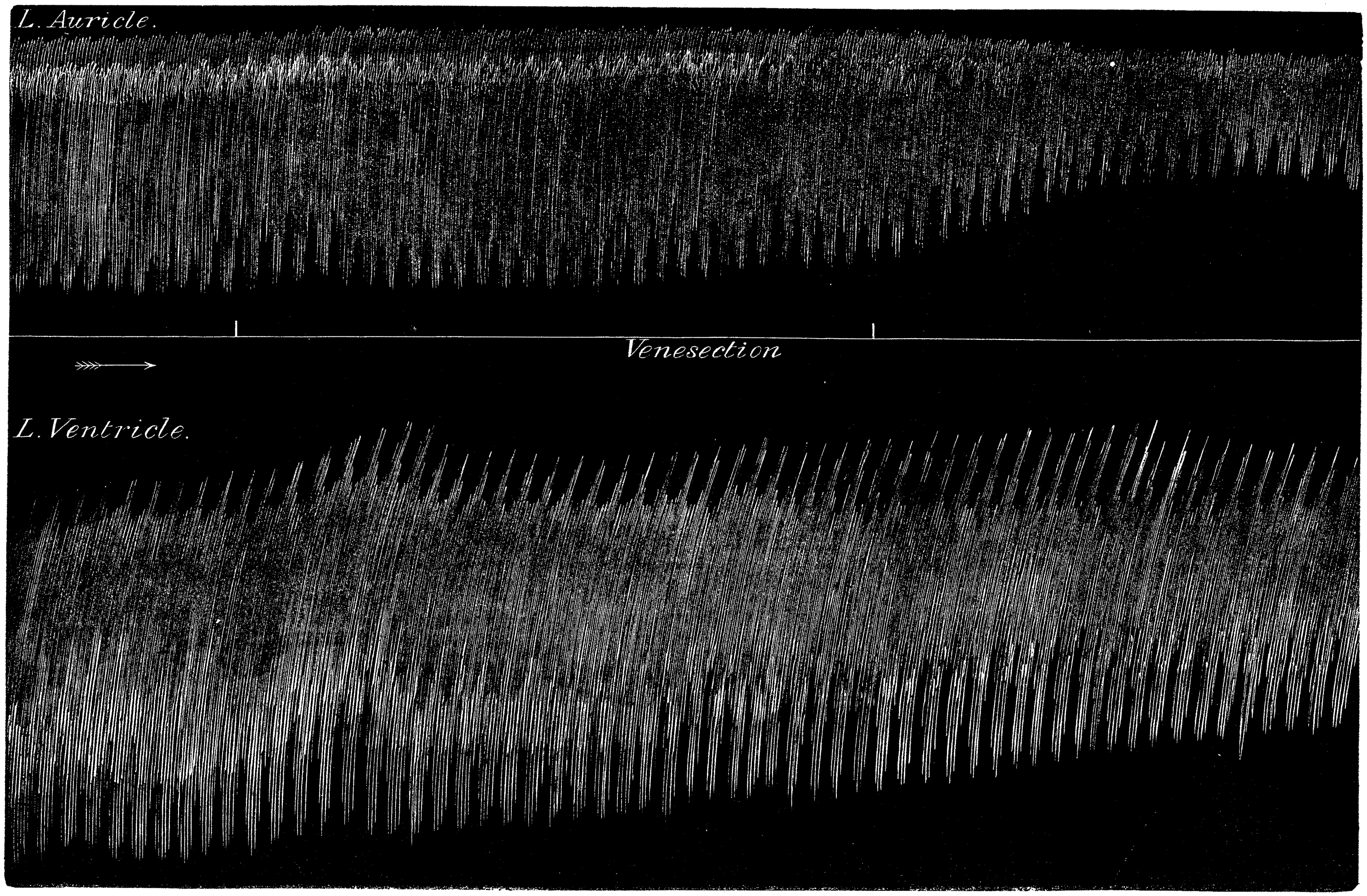
when it is found that the force of both the auricular and ventricular contractions is markedly diminished. If, now, the blood which has been removed be reinjected, the force of the contractions both of the auricle and ventricle returns more or less exactly to that which was shown by the myocardiographic curve before the blood was "let." This change is well exhibited in Figs. 31 and 32, from a medium-sized Dog. In both figures the ventricular tracing is above, the auricular below, and contraction pulled the lever point down. Fig. 31 shows the effect of removing 120 c.cm. of blood from one of the carotids. The ventricular contraction, as can be seen, becomes diminished in force in spite of the fact that the lowered blood-pressure, offering less resistance to the contractions of the left ventricle would of itself have led to increased systolic contraction; the ventricle also shows slight increase in the degree of diastolic expansion. The auricular tracing shows marked diminution in force of the contractions, which does not, however, go hand in hand with the weakening of the ventricle, but follows a curve of its own. In Fig. 32, taken from the same heart a few minutes later, can be seen the effects of reinjection of the blood which had been removed, and which, during the interval, has been defibrinated and kept at the body temperature. As the curve shows, the force of the ventricle is markedly increased: it must be understood, however, that the tracing does not show the whole of the resulting increase, as it still continued to improve for some little time afterwards. The auricular tracing shows an increase of force, the lower or systolic margin descending with a curve which resembles that obtained on removing the blood, save that in the one case the curve descends, in the other it ascends.

These curves sufficiently show the effect of changes in the pressure of the blood upon the strength of the contractions of the auricles and ventricles, and we therefore conclude that *a rise of pressure in the systemic arteries causes an increase in the force of the heart's contractions, which* MAY *more than counterbalance the increase in the resistance to the contractions of the left ventricle which that rise introduces, so that the ventricle may contract more completely than it did before the pressure was raised, and also, that a fall of pressure may diminish the force of both auricular and ventricular contractions, and may lead to an increase in the amount of residual blood contained in the ventricle.* It is necessary to add, in so far as concerns the ventricular tracing, that Figs. 31 and 32 show an unusually marked effect of anæmia upon the force of the heart's contractions, and that in many of our experiments the weakening of the systole did not counterbalance the diminution of resistance due to the fall of blood-pressure, so that the residual blood was diminished in amount.

(*b*.) Effect of Varying the Volume of Blood in the Body upon the Contraction Volume and Output of the Heart.

If, having applied the cardiometer to a dog, and obtained records of the contraction volume and output of the heart, we now inject into the veins measured quantities of warm defibrinated blood obtained from another dog, the effect upon the curves is

Fig. 31.



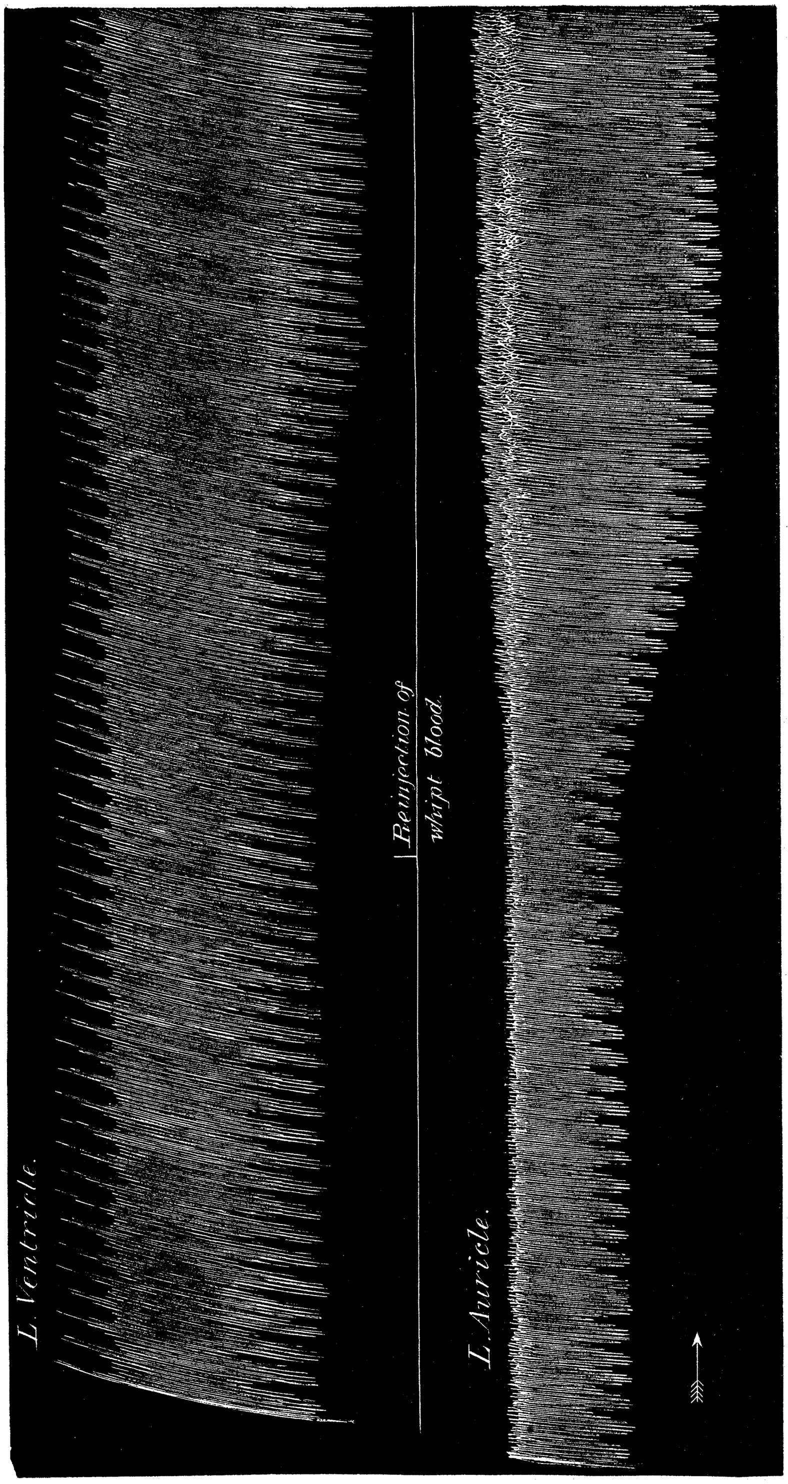
Myocardiographic tracings [original size] from L. Ventricle (above) and Auricle, contraction causing downward movement of the lever points. The tracings show the effects of removal of blood from the jugular vein. There is marked weakening of the auricular and ventricular beats in consequence. The escape of blood began at the first mark on the signal curve and ended at the second mark.

very striking. In the first place, the rate of beat remains unchanged, the contraction volume, and therefore—as there is no change of rhythm—the output of the heart, is increased to a degree which is quite disproportionate to the amount of blood introduced. For example, in a medium-sized dog, injection of 100 c.cm. of whipped blood will often double the output and contraction volume. In other words, with a dog of a weight of 12 or 13 kilos., and whose blood, therefore, we may assume to be about 1,000 c.cm. in amount (according to the usual computation that the blood is equal to $\frac{1}{13}$th of the body weight), the injection into the veins of an additional volume of blood equal to $\frac{1}{10}$th of the total blood of its body, may double the amount of blood thrown out of the heart in a given time. This increase in the output, moreover, lasts for some time, as long, in fact, in our experiments as the condition of the animal remains unchanged; it is always accompanied by an increase in the volume of residual blood, and differs, therefore, in so far from the effects of re-injection into an animal of blood which had previously been removed.

It took us a long time to distinguish clearly between increase in force of the contractions of the heart due to increased supply of blood to the coronaries, and that due to the action of the augmentor nerves. When the systemic blood-pressure is below normal, injection of blood into the veins may improve the nutrition of the heart wall to an extent which more than counterbalances the increased resistance to contraction of the left ventricle resulting from the rise of pressure in the systemic arteries, so that, as in the example shown in Fig. 32, the amount of residual blood in the left ventricle is diminished. When, however, the blood-pressure is about the normal mean for the animal, injection of defibrinated blood raises the venous pressure, increasing thereby the input and output of the heart without any corresponding rise of the arterial, and therefore of the coronary pressure, so that the work of the heart is increased without any accompanying improvement in its nutrition. The result of this is that the contractions are less complete, and the residual blood in the ventricles is increased in amount. The unravelling of the relationship between the force of the heart's contractions and the nutrition of its walls was, in our work on the subject, rendered still more difficult owing to the fact that improvement in the nutrition of the heart wall often leads, not only to increased force of contraction, but also to increased frequency of beat. According to our experience, the characters of the myocardiographic curves suffice in most, though not in all, cases to enable one to distinguish between "augmentor" effects and increase of force of contraction due to improved nutrition of the heart substance resulting from rise of the aortic blood-pressure.

That the great increase in the output of the heart, resulting from a relatively small addition to the total volume of the blood, does not cause a rise of pressure in the systemic arteries, must be due to relaxation of the vessels of some vascular area or areas, and it is important to note that *the output of the heart may be doubled, or*

Fig. 32.



From the same animal as Fig. 31 taken a few minutes later, and showing the strengthening effect of reinjection of the blood which had been removed.

trebled, or more, without the blood-pressure in the systemic arteries rising above the normal mean for the animal.

It must be kept in mind, however, that increase of the output, such as results from increasing the total volume of the blood in the body, increases to a corresponding degree the work done by both ventricles, and, also, that if there be such a thing as plethoric hypertrophy of the heart, it must affect both the right and left ventricles, while hypertrophy due to rise of blood-pressure in the systemic arteries will, in the absence of mitral insufficiency be confined to the left ventricle.

(c.) *Upon Artificial Hydræmia and its Effects.*

A condition of artificial hydræmia may be produced by injecting into the circulation a warm 0·75 per cent. solution of sodium chloride. The effects on the heart of hydræmia so brought about are shown in the myocardiographic curves of Fig. 33, which shows the successive changes in the left auricle and ventricle produced by injecting 240 c.cm. warm normal salt solution into the veins of a medium sized dog. We have cut out portions of the curve in order to economise space, and it must be understood that in each of the intervals, some two to four minutes in duration, 60 c.cm. of the solution had been introduced. The upper curve is from the left auricle, the lower from the left ventricle, contraction in both cases causing a downward movement of the lever point.

With regard to the ventricle, it can be seen that the degree of expansion in diastole is increased, as is shown by the rise of the upper limit of the tracing, and, also, that the degree of the contraction in systole is lessened, so that there is, therefore, an increase in the amount of residual blood. We cannot conclude from this tracing that the *force* of the ventricular contractions has been diminished, seeing that the expansion in diastole is increased, which *of itself* necessarily leads to a less complete contraction in systole. Nevertheless, there is here a dilation of the ventricles.

With regard to the auricle, the degree of expansion in diastole is unchanged by the hydræmia; the degree of contraction in systole is, however, markedly reduced.

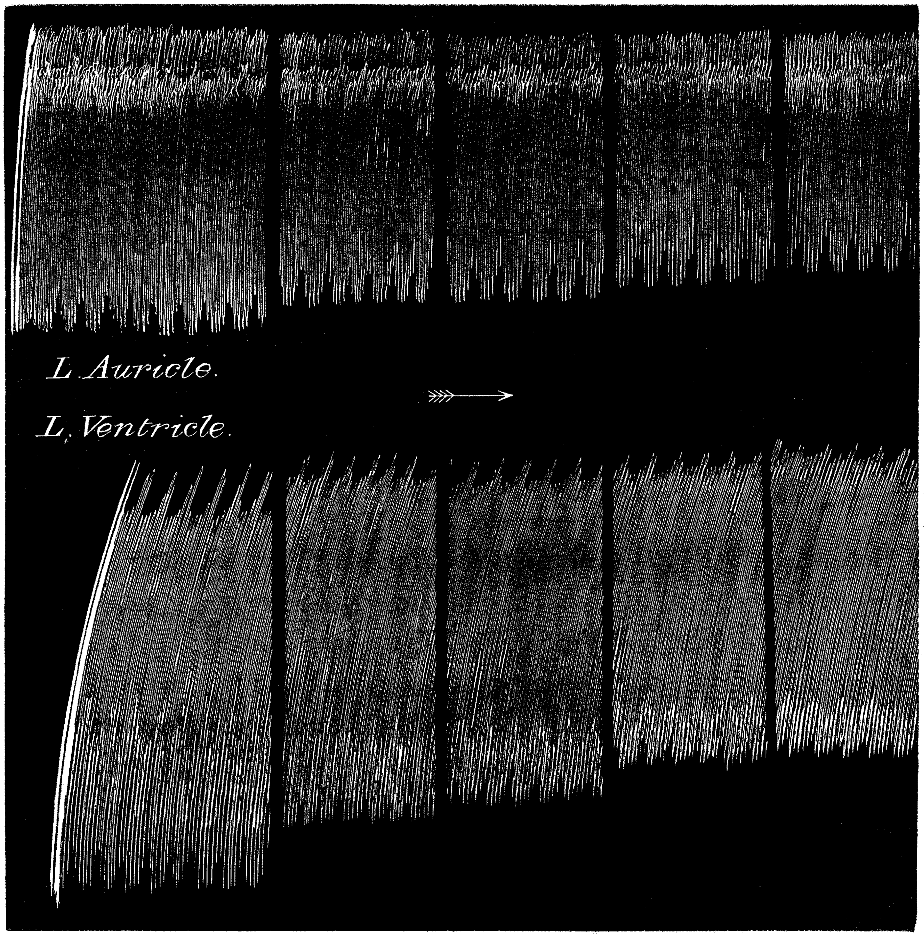
There is, therefore, unmistakable weakening of the auricles, and presumably also of the ventricles, seeing that the effect of changes in the total volume of blood is usually the same for both.

With the help of the cardiometer we find that injection of salt solution into the veins causes the same increase in the contraction-volume and the output which is produced by injecting defibrinated blood, so that it is very easy to double or treble, or even quadruple, the amount of blood which passes through the heart in a given time. There is, however, this important difference between the two, namely, that the increase in output due to artificial hydræmia is of much shorter duration than that due to injecting blood into the veins.

In Fig. 36 is shown a cardiometer tracing illustrating the effects of injecting

50 c.cm. of warm normal salt solution into the jugular vein of a medium-sized dog. The part A shows the volume of the heart before injection, B that after injection of 30 c.cm. and C after a further injection of 20 c.cm., making in all 50 c.cm. The rate of beat is not appreciably altered, and the increase in the contraction volume, and, therefore, of the output in C as compared with A is about 34 per cent.

Fig. 33.



Myocardiographic tracings [original size] from L. Ventricle (below) and L. Auricle (above); contraction caused downward movement of the lever-points. To show the effect of injection into the circulation of successive amounts of warm normal salt solution; during each interval upon the figure 60 c.cm. of salt solution was injected into one of the jugulars. The auricular contractions are weakened; the diminished contraction in systole, and increased expansion in diastole of the ventricles, are well seen.

The cause of the increased output in this experiment is not far to seek; it is evidently brought about by the rise in pressure in the large systemic veins, which increases the amount of blood passing through the tricuspid orifice. It is important to note how greatly the output of the heart may be varied by changes in the pressure in the systemic veins. As we have pointed out elsewhere, by very gently pressing

the abdominal wall with the hand, and thereby diminishing the amount of blood in the veins of the abdominal cavity, the output of the heart is greatly increased, in some cases by as much as 50 per cent. It must be kept in mind, therefore, that every muscular movement which involves contraction of the muscles of the abdominal walls must cause, in the same way, an increased flow of blood into the heart, and, therefore, a correspondingly increased output. The same also applies, though to a lesser degree, to the slight compression of the abdominal viscera produced at each inspiration by the descent of the diaphragm.

We have seen that in artificial hydræmia, although the work done by the heart may be doubled or trebled, the force of the contractions of the auricles and ventricles, instead of being increased in order to cope with the increased work thrown upon the organ, is diminished. This weakening of the heart may be satisfactorily explained by the thinning of the blood which passes through the coronary vessels, and a similar condition must necessarily be present in hydræmia due to disease.

Hydræmia due to Disease.

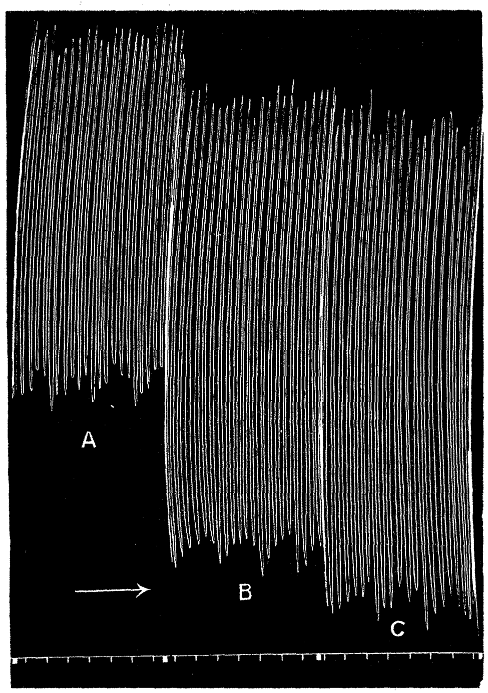
It is not difficult, therefore, to understand the pathology of heart-failure in chlorosis, or in other diseases where the specific gravity of the blood is reduced, and where there is therefore a diminution of the solid constituents of the blood. In such cases the food supplied to the heart is of diminished nutritive value, while the work which the organ has to perform is not reduced to a corresponding extent, but is, indeed, very frequently increased. That the heart in these conditions may easily become so dilated that functional regurgitation through the mitral and tricuspid orifices manifests itself is only what one would expect. Seeing that increase in the output of the heart will not of itself put the left ventricle to a greater disadvantage than the right ventricle, the fact that the mitral valve often gives way before the tricuspid, would seem to indicate that, in chlorosis, the pressure of the blood within the systemic arteries is frequently higher than normal.

The readiness with which the heart is quickened on slight exertions and emotions in the case of chlorotic patients, shows how readily the augmentors are called into play in that condition, and if, as may be assumed, the pressure in the systemic vessels is at the same time raised by constriction of the vessels of certain vascular areas, we can readily understand that more work will be thrown on the left heart than upon the right. It must not be forgotten, however, that mitral regurgitation, due to malnutrition of the heart, differs from that caused by organic valve disease, in so far as in the former the right heart has also been badly fed as well as the left, so that we would expect tricuspid regurgitation to follow much more closely upon the mitral insufficiency of chlorosis than upon the regurgitation of organic mitral disease.

The enormous increase in the work done by the heart which results from the injection of a comparatively small amount of normal salt solution, shows how important

it must be to reduce to the lowest possible limit the water of the food and drink of patients suffering from weak or diseased hearts. Since we have touched in passing upon the treatment of heart cases, it may be well to say a few words upon the subject of muscular exertion. This, as we know, throws upon the heart the maximum amount of work which it can be called upon to do under normal physiological conditions, at the same time, by means of the augmentors, increasing to the maximum extent the force of the heart's contractions; and so closely is the heart concerned in muscular exertion that the energy and endurance of an individual are really limited by the power of the heart to supply the increased amount of blood which the

Fig. 34.



Cardiometer tracing [original size], contraction causing *upward* movement of the lever-point. Between the parts A and B, 30 c.cm. of warm normal salt solution were injected intravenously, and between B and C, 20 c.cm. more [50 c.cm. in all]. The increase in the contraction volume and output are well shown. The Dog was of medium size.

contracting voluntary muscles require. Now there is plenty of evidence to prove that, when the nutrition of the body is not below "par," repeated severe exertion leads to cardiac hypertrophy, as it does in the case of other muscles of the body, and also that the strength of the heart increases to an extent corresponding to its increase in weight. In the case, however, of a person with hydræmia and a weak heart, any increase of the work thrown upon the organ simply increases the disadvantages under which the heart already labours. Graduated exercise may be good in some cases of heart disease, but if the specific gravity of the patient's blood be

below normal, any exertion must tell unfavourably on the heart to a degree corresponding with the thinness of the blood.

As has been shown by LLOYD JONES,* failure of compensation in heart disease is usually associated with a considerable fall of the specific gravity of the blood. What we have said above on the effect of hydræmia on the heart may serve to emphasise the importance of watching the specific gravity of the blood in heart cases.

SECTION XIV.—THE STRENGTH OF THE LEFT VENTRICLE IN RELATION TO ITS WORK.

The nerves of the heart only partially control the amount of work performed by the organ. The amount of blood which enters it is largely dependent upon the pressure within the systemic veins, which is a very varying quantity; the pressure also in the systemic arteries depends, not only on the amount of blood which enters the aorta, but also upon the freedom with which the blood can escape from the systemic arterioles, a matter which is under the control of the vasomotor mechanisms. When, under physiological conditions, *e.g.*, active exertion, the work thrown upon the heart is increased, partly by increase in the amount of blood which reaches it from the veins, and partly by rise of the arterial pressure due to constriction of the vessels of certain vascular areas, the force of the ventricular beats is, at the same time, increased by the action of the nervi augmentores, with, at the same time, in certain cases, an increased rapidity of rhythm. As we have pointed out, the increase in the work performed by the heart is not absolutely proportionate to the increase in the force of the heart's contractions, the result of which is, as shown in our curves, Figs. 24, 25, and 26, that sometimes the increase in force of the ventricle more than counterbalances the heightened resistance to contraction of the left ventricle due to the increased contraction-volume and rise in pressure in the systemic arteries, so that this part of the heart contracts more completely, having less residual blood than was the case before the work was increased. In other cases, on the other hand, the increased force of contraction of the left ventricle does not fully counterbalance the increased work which is thrown upon it, and the ventricle does not contract so completely against the increased resistance, so that the amount of residual blood is increased. In other words, the increase in force due to the augmentors does not prevent the heart undergoing a certain degree of dilation.

This physiological dilation, in spite of augmentor action, must be sharply distinguished from the physiological dilation which may be produced without accompanying augmentor action, *e.g.*, by increasing the total volume of blood, or by intravenous injection of salt solution.

It requires no reasoning or reference to special experiments, although we might

* "Specific Gravity of the Blood in Health and Disease," 'Journal of Physiology,' vol. 12, 1891, p. 299.

quote such, to prove that the weaker or more fatigued a given heart is, the more does this physiological dilation due to exertion show itself. The more fatigued a heart is, the less is it able to cope with increased work thrown upon it by mechanisms whose action has not been weakened to the same extent. It is easy to understand, therefore, why it is that even in the perfectly healthy individual the heart only for a short time can cope with the greatly increased work thrown upon it by active muscular exertion, and why it is that very soon, even with maximum action of the augmentors, the heart becomes fatigued and, therefore, dilated, and that in most cases this fatigue of the heart limits the degree and endurance of muscular exertion. The heart can, as we know, by judicious training be greatly strengthened, so that its force of contraction effectively counterbalances for a longer period the increase in work which is thrown upon it during exertion, and there is some evidence that this increase in the power of the heart is, in part, due to hypertrophy of the ventricles (as strictly physiological as is that hypertrophy of the muscles of an athlete, and as is the "blacksmith's arm," which resembles cardiac hypertrophy in so far that, in both cases, the affected muscles are more liable to undergo regressive metamorphosis than are unhypertrophied muscles). That training is mainly a matter of the heart is shown by the fact that those articles of diet, or luxuries, such as tea, alcohol, tobacco, and excessive consumption of fluids, which are strictly limited in training, all either primarily weaken the heart or increase the work thrown upon it without corresponding improvement of its nutrition. Alcohol, as we will show elsewhere, causes primary weakening of the ventricular contractions, and, if given in large enough dose, induces dilation, which, in itself, without any increase in the work, may lead to functional incompetence of the auriculo-ventricular valves. How small a quantity of alcohol will suffice to prevent prolonged or severe exertion is well known, for example, to such Alpine climbers as have once, in an unguarded moment, taken some brandy or whiskey in the middle of a long day. We do not believe that Alpine climbers ever repeat this experiment. Nicotine also acts on the heart like alcohol, causing primary weakness and dilation of the ventricles, and the same is the case with caffein, although the latter is not so deadly a heart poison. It must be understood, of course, that in moderate doses the effects of all these luxuries upon the heart may be more than counterbalanced by their beneficial action on the rest of the economy, but it must be kept in mind that, under conditions where the heart is to be driven at high pressure, the less these luxuries are used the better will the organ be able to carry on its work. We have already pointed out the unfavourable action of hydræmia upon the heart, and need not insist upon the reduction of liquids in training or during severe exertion.

It must be understood that what we have said above, as to the limits of the heart's power in health, applies equally, or even more strongly, to cases where, from disease or other form of malnutrition of the heart, the organ habitually works close to its maximum limit. The increase in its work which the heart at any given time is capable of compassing, is sometimes referred to as the "*reserve force*" of the heart.

We must be clear upon this point, as in spite of much laborious work by physiologists, the nature of the heart's action is not always by any means clearly recognised by clinicians. In the first place each ventricular contraction is a maximal one, that is to say, is the greatest which the ventricles have the power of producing in the condition of their walls for the time being. This has been clearly recognised for the ventricles of cold-blooded animals, and from our own observations we are convinced that it applies equally to the Mammalian heart, auricles as well as ventricles.* The strength of the contractions can be altered by a variety of causes, in some of which the heart is, so to speak, passively affected, in others, by means of its nerves, active changes are produced. Of the passive ones we may mention firstly, the composition of the blood, and the pressure of the blood in the coronary arteries. We have referred to this above, and need not say any more here than that it has an extremely important effect on the force of the heart's contractions. Secondly, the force of the contractions is influenced by the rate of beat; the contractions will be most powerful with some particular rate of beat, presumably to the same extent as in cold-blooded animals, and independently of any action of the nerves. On this subject we can say little from direct observation on the Mammalian heart; we can only say that the heart appears capable of beating within wide limits as regards rate, without any very obvious change in the force of its contractions. A third influence is the temperature, but on this we have made no direct observations.

It is important to note that changes in the pressure of the blood in the large veins or in the amount of blood which enters the heart during diastole, do not directly alter in the slightest degree the force of the ventricular contractions. This does not prevent the amount of work done by the ventricles varying within very wide limits without any corresponding change in the force of their contractions. What happens, simply is, that change in the work done by the ventricles at each contraction changes the degree to which they contract in systole.

If the amount of useful work to be done at each contraction be very far below the power of the ventricle, at the time, to perform the work, a certain part of the energy of the contractions, which, as we have seen, are always maximal, will be "wasted," and will appear mainly as distortion of the elastic constituents of the ventricle wall itself. This is the necessary result of the reduction of the work performed by the muscle below the energy expended during contraction, some of the excess of energy being transformed into heat. The "waste" of energy in either case will be partly given back with commencing relaxation, the distortion causing the elastic resilience which leads, under certain circumstances, to the production of a negative pressure in the ventricles during a certain phase of diastole. If the "useful" work to be done by the ventricles be increased, a smaller part of the energy of the contractions will be

* McWilliam, 'Roy. Soc. Proc.,' comes to the same conclusion, although the methods employed by him are, according to our experience, unfitted to give trustworthy information on the force of the ventricular contractions.

employed in producing distortion or be transformed into heat. If the aorta be closed for an instant the intra-ventricular pressure may be raised during systole to over 300 mm. of mercury, the work done by the ventricle may also be increased by increase in the contraction volume, without, in either case, the total energy expended in contractions being increased. What happens is, that the ventricular wall contracts less completely, exactly in the same way as a voluntary muscle excited to contraction by maximal stimuli lifts a heavy weight a shorter distance than it does a lighter weight. There is, however, and can be, no diminution of the output of the heart, putting aside for a moment the residual blood, unless there be regurgitation through auriculo-ventricular valves. The importance of this subject must be our excuse for insisting upon it.

The force of the ventricular contractions can be varied *actively* by the nervi augmentores, and, to a limited extent, by the vagi, and it is by these nerves, as well as by the changes in pressure in the coronary arteries that the force of the heart's contractions are varied, in accordance with the variations in the work thrown upon it. As we have seen, however, these nerves are not necessarily called into play by all the causes which change the work of the heart, for example, by alteration in the venous pressure due to removal, or injection, of blood from or into the veins. Yet, even when the nervi augmentores are called into play, as is the case with the typically physiological increase in the heart-work accompanying muscular exertion, it does not follow that the ventricle will be sufficiently increased in strength to cope with the increased work thrown upon it, and *the ventricle, like every other muscle in the body, is liable to fatigue, so that the force of contraction obtainable by maximum augmentor action becomes less and less when the heart continues to put forth its maximum efforts.* In this matter the heart appears to differ in no respect from other muscles. The heart, whose walls have been weakened by disease or malnutrition, not only beats more feebly in the absence of any augmentor or vagus action, and contains, therefore, habitually a larger amount of residual blood than that of a healthy, well-nourished person, but is also less able to meet increased calls upon its powers, so that the increased force due to augmentor action is always less than is required to counterbalance the increased work demanded from the heart, and therefore failure shows itself first during moments of exertion. It must be kept in mind that the strain on the heart wall in systole, which is overcome by, or rather is due to, the contraction of its walls, increases with the circumference of these walls, so that a rise of pressure in the systemic arteries throws a greater strain on the walls of a dilated left ventricle than on the walls of an undilated heart. Even were we to assume that the augmentors were capable of producing an equal increase in force of contraction in both cases, and if this increase in force exactly counterbalanced the increase in resistance in the undilated heart, so that the ventricle had neither more or less residual blood than before, it would be different in the dilated heart, as to the strain due to the rise of pressure must be added that due to increased circumference, and the ventricle would therefore contract less completely, and the

amount of residual blood would be increased. In other words, a dilated ventricle is *per se* unfavourably placed for meeting an increase in the work thrown upon it. We cannot, however, assume that the augmentors have the power of increasing the force of contraction of a diseased, weakened, or fatigued ventricle to the same extent as that of a healthy one.

It is easy to understand then, why a diseased heart gives way first during moments of exertion, in spite of the action of the augmentors. It must be assumed, also, that prolonged or extreme augmentor action causes, as in the case of maximal contraction of other muscles of the body, fatigue which will not only lessen the force of these maximal contractions, but will in the case of the heart, for a time varying with the nutrition of the individual, diminish the force of the ventricular contractions which are carried on after the augmentors have ceased to be excited. We would expect, therefore, that a heart whose powers had been overstrained, would remain dilated for a varying time after the work thrown upon it had ceased to be increased. There is nothing in this contradictory to the fact that, with repeated great augmentor action, under favourable conditions, the heart becomes hypertrophied. This is only what takes place in the case of all muscles of the body. In a healthy heart, whether there be augmentor action or no, *dilation and fatigue are synonymous terms: in a diseased heart the degree of dilation of its cavities is in inverse ratio to its power of doing its work; in both cases the dilation* per se *places the heart in an unfavourable position for meeting physiological increase in the work thrown upon it.*

We have said nothing, so far, about the part played by the vagus in protecting the heart against overstrain or fatigue. Even in the greatly weakened heart of, let us say, chlorosis, active exertion is accompanied by augmentor action; the vagus does not therefore completely prevent the heart responding to demands on the part of the system for more blood, and does not therefore prevent the heart being thereby fatigued. In practically all cases, however, where the heart is so greatly overworked that the limits of its powers are approached, or where from malnutrition or disease the power of the heart is limited without corresponding reduction of the work thrown upon it, there is no want of evidence of increased intervention on the part of the vagus. Of this intervention one of the effects is cardiac irregularity.

Irregularity of the Heart.

Leaving out of account the vermicular contractions which accompany acute death of the heart, we may distinguish two main varieties of cardiac irregularity, that, firstly, which results from vagus action, and that due to local excitation of the heart wall. The latter may produce, as Einbrodt* showed, extreme irregularity of the ventricles, different parts of the ventricular wall contracting rapidly but independently of one another. This form of irregularity may possibly manifest itself in some

* Einbrodt, *loc. cit.*, p. 347.

cases of disease of the heart, but must be very rare in comparison with what we may call "*vagus irregularity.*"

That excitation of the vagus nerve may produce irregularity of the heart was discovered by WEBER and JACOBSON so long ago as 1847.* It was supposed by them to be due to unilateral stimulation of the nerve; LUDWIG and HOFFA, however, pointed out in 1850 that this view was erroneous, as irregularity of the heart is produced also by simultaneous stimulation of both vago-sympathetics. Since that time the connection between vagus activity and irregularity of the heart seems to have been generally passed over, although it was kept in mind by some. For example, COHNHEIM† knew that the irregularity of the dog's heart which is so commonly met with, could if desired, in the case of its interfering with an experiment, be stopped by section of both vagi. He, however, knew, and could know, nothing as to the manner in which the vagus produces irregularity of the heart. Our own observations upon the effect of vagus excitation show clearly enough how the irregularity is brought about. The vagus weakens the force of the auricular contractions, and, as we must conclude from our curves, lessens to a corresponding degree the strength of the rhythmic excitations which reach the ventricles from above, and at the same time it diminishes the excitability of the ventricles, but, in spite of the latter the ventricles tend to take up a rhythm of their own which is slower than the normal beat. If the strength of the current applied to the vagus be gradually increased, the stimuli which reach the ventricles with each auricular contraction become weaker and weaker, while the ventricles in the absence of sufficiently strong stimuli reaching them from above begin to take on their own independent rhythm. Each rhythm alone is regular, but when they both affect the ventricle at the same time, there is interference and irregularity. Interference of the two rhythms, however, is not essential for vagus irregularity; simple intermissions of the pulse may result from the weakened auricular impulses not being followed in all cases by a ventricular contraction, and in this way may be produced a bi-, tri-, or quadri-geminal or other variety of intermittent pulse. When the independent ventricular rhythm is superposed on the usual rhythm, arhythmic irregularity is more commonly met with, although here, also, rhythmic irregularity may be produced. The above are the most common forms which we have met with in the Dog, but some of our tracings would seem to show that during vagus action the auricles do not always respond to the impulses which reach them from the sinus. We have tracings which seem to show, also, that in some cases of poisoning when the heart is dying, irregularity may in these cases be due to derangement of the rhythmic centre.

When, in gradually advancing heart disease, intermissions of the pulse show themselves along with a somewhat slowed rhythm, we have a reproduction of what

* E. WEBER and JACOBSON, "Quæstiones de Vi Nervorum vagorum in Cordis Motus." Halæ Saxonum, 1847. Referred to by LUDWIG and HOFFA, "Zeitschr. f. rationelle Medicin," vol. 9, 1850, p. 116.

† Verbal communication.

takes place on moderate stimulation of the vagus: the ventricles omit to follow the auricles at what may be very regular intervals In these cases the vagus is continually acting on the heart with a somewhat more powerful influence than is exerted by it in the healthy individual, and the extent to which the vagus activity habitually affects the heart will presumably correspond in degree with the demands of the organ for diminished work. It must not be forgotten, however, that the relation between the degree of vagus action and the needs of the heart will only apply in cases in which the nervous mechanism of the organ continues to act normally, and will not apply, for example, in those cases of extreme slowing or quickening of the heart which are not necessarily associated with disease or weakness of the heart muscle, and which may be of a purely nervous nature.

We would expect these vagus intermissions to disappear whenever, through excitement or exertion, the nervi augmentores are called into play, since vagus irregularity is stopped by these nerves.

Another form of vagus irregularity is that where a bigeminal beat is inserted at regular or irregular intervals. In these cases, if it be not an extreme form of intermittent pulse of the kind just referred to, it is due to interference of the auricular and ideo-ventricular rhythms, and indicates either a greater vagus action, or an increased excitability of the ventricles, from disease or malnutrition of its walls.

In the extreme form of irregularity, which is sometimes called *delirium cordis,* it may safely be assumed that the vagus has lost control over the ventricles, that these are contracting independently of the auricles, and also that the excitation, or excitability, or both, of the ventricles have become increased. When such extreme irregularity occurs in the Dog we have found that the ventricular wall and musculi papillares may cease to contract synchronously, and also that, in extreme cases, the different parts of the ventricular walls may contract asynchronously.

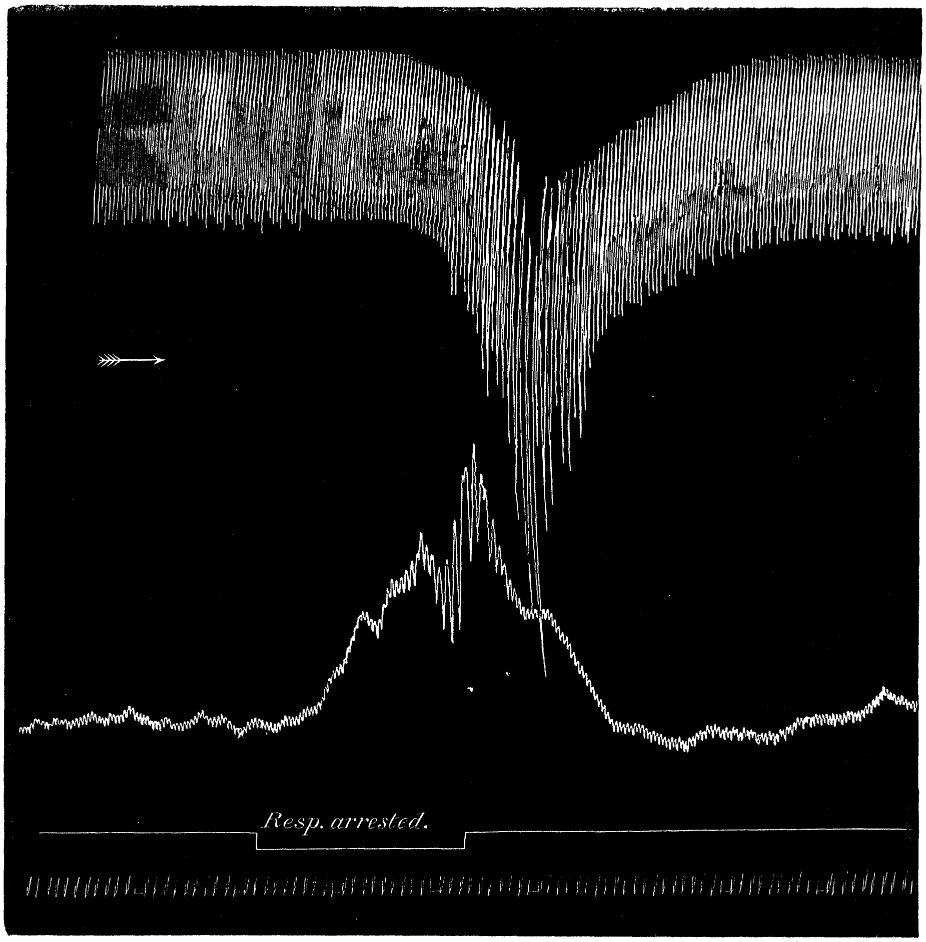
The effects of irregularity on the heart may be put very concisely: the irregular heart expends more energy for a given amount of work than a regular heart; when a heart becomes irregular its output, other things being equal, is diminished. In cases where the irregularity does not extend beyond an intermission every tenth beat or so this is not an important matter, but, with the great irregularity which occurs in advanced heart cases, this change in the relation between work performed and energy expended, becomes an extremely serious element in the vicious circle which is brought about as soon as so-called failure of compensation takes place.

SECTION XV.—EFFECT OF IMPERFECT AËRATION OF THE BLOOD UPON THE HEART.

The effect upon the heart of imperfect aëration of the blood is, for obvious reasons, a subject of much importance. It can be conveniently studied experimentally by arresting for a short time the artificial respiration in animals whose voluntary muscles have been paralysed by curare.

With regard, first of all, to the effect of temporary asphyxia on the output and contraction-volume of the heart, we may refer to Fig. 35. The upper of the two tracings is from the cardiometer, upward movement of the lever-point corresponding with a diminution of the volume of the heart, so that the upper margin of the curve represents graphically the volume of the heart at the end of systole, while the lower margin gives the maximum diastolic volume, the distance between the upper and lower extremities of each of the up and down lines expressing the contraction volume. The other tracing in the figure is a blood-pressure curve from the carotid artery, taken simultaneously.

Fig. 35.



Cardiometric and blood-pressure tracings, contraction in the former case causing upward movement of the lever point. The tracing shows the effect of arrest of respiration on the contraction volume and size of the heart in systole and diastole.

It can be seen that, in this case, after twenty or so beats, the heart began to become more expanded both in systole and diastole, the rhythm becoming gradually slowed. It is to be noted, also, that the increase in the diastolic volume of the heart is more than double the maximum increase in the systolic volume, the fall in the

lower margin being equal to 62 mm. while that of the upper margin is equal to only 27 mm. This increase in the contraction volume is due mainly, if not entirely, to the slowing of the heart, which it more or less exactly counterbalances. The blood-pressure shows the rise which is usually produced by slight asphyxia, the work of the left ventricle being increased to a corresponding extent.

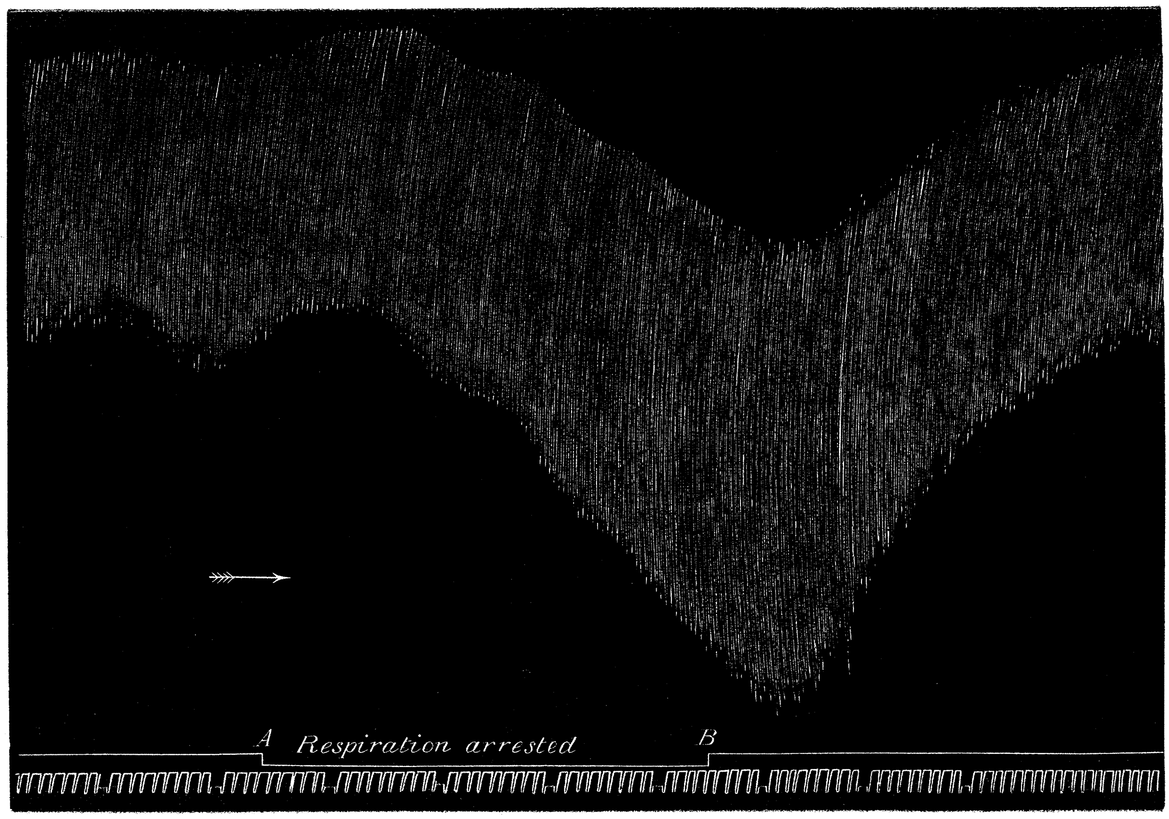
If the respiration be interrupted for a somewhat longer period, the output usually however, becomes markedly reduced: for example, in one experiment before interrupting the respiration, the time required to expel 100 c.cm. of blood from the heart was 3·5 seconds, while, during the asphyxia, 5·7 seconds was required to expel the same volume; the number of beats fell from 27 in 10 seconds to 16 in the same period during the interruption of respiration. In another experiment the number of seconds required for the expulsion of 100 c.cm. of blood was 4 seconds before, and 7 seconds during, arrest of the respiration. In many cases, though not in all, the diminution of the output during asphyxia is followed by an increase in the output lasting for a minute or two after the recommencement of the respiration; for example:—

	Time of expulsion of 100 c.cm. in seconds.	Number of beats in 10 seconds.
A. Before Asphyxia . .	4·4	29
During " . .	5·0	21
After " . .	4·0	28·5
B. Before Asphyxia . .	4·3	30
During " . .	5·5	21
After " . .	3·5	29

That these effects are mainly due to vagus action is at once evident from the effect of cutting through both vago-sympathetics, and finding how this affects the phenomena which result from arrest of the artificial respiration. A cardiometer curve obtained under these conditions is shown in Fig. 36. The respiration is interrupted at *A* and recommenced at the point *B*. It can be seen that here, also, there is a marked increase in the volume of the heart during systole, and one still more marked in the volume during diastole, the former being increased to an extent equal to about 40 mm. as measured on the tracing, while the latter is increased to an extent equal to about 74 mm. As there is no change in the rate of beat, this involves an increase of the output corresponding to the increase in the contraction-volume, which rises from about 45 mm. upon the tracing before arrest, to a maximum of 75 mm. at the end of the period of arrested respiration. This tracing shows that the increase of systolic and diastolic volumes is not due entirely to the action of the vagus fibres upon the heart as might, perhaps, be supposed from an examination of Fig. 35, but that it is due to some other effect upon the heart of interference with the aëration of the blood.

Before enquiring further into this matter, we may conclude from the above that, *in the curarised animal arrest of the respiration, the vago-sympathetic nerves being intact, causes excitation of the vagus mechanism and a diminution of the output of the heart; that the effects of asphyxia upon the heart, after these nerves have been cut, is to produce expansion of the heart both in systole and in diastole, and that the latter may greatly exceed the former of these in amount, so that the contraction volume may be greatly increased, involving, in the absence of any change in the rate of beat, a corresponding increase in the output.* The occurrence of this relaxation of the heart after section of the vago-sympathetics shows that it is not due exclusively to the action of these nerves upon the organ.

Fig. 36.



Cardiometric tracing [two-thirds original size], contraction causing upward movement of the lever point. The beginning of the tracing shows TRAUBE-HERING waves. On stopping the respiration, (the vagi having been previously cut), the contraction-volume of the heart becomes increased, the organ at the same time becoming dilated both in systole and in diastole. [The contraction-volume during the period of maximum effect is nearly double what it was before the respiration was arrested. As there is no change in the rate of heart-beat, the output was increased to the same extent.]

What we have stated above is the usual effect of temporary asphyxia upon the output of the heart in curarised animals, but we have met with cases where, in spite of the vagus action, the output of the heart has been increased. Sometimes temporary

asphyxia is unaccompanied by any marked change in the output, as in the cardiometric tracing in Fig. 37, where there is very marked expansion of the heart, but little or no change in the contraction-volume and output. The cause of these differences in different experiments is, we believe, ascribable to differences in the effect of temporary asphyxia upon the pressure in the systemic veins. When, as is sometimes the case, the venous pressure is very high, it may cause the output of the heart to be increased in spite of well-marked vagus effect. In the uncurarised animal the powerful muscular movements which take place in asphyxia would certainly raise the venous pressure to a height which would tend to increase the output of the heart in spite of the activity of the vagus, which, did it act alone, would tend to reduce the output.

In Fig. 38 is shown a simultaneous graphic record of the contractions and expansions of the auricular and ventricular walls respectively. In the two curves, auricular above, ventricular below, from the heart wall, downward movement of the lever point corresponds to contraction, so that the lower margin of the curve represents the degree of contraction in systole, the upper margin the diastolic expansion.

The curve shows that interruption of the respiration, even for a short period—in this case for only about one minute and a half—produced a great diminution in the force of the auricular contractions, without, however, causing more than a very slight increase in the expansion of the auricular wall, while the ventricle becomes less contracted in systole, and more expanded in diastole, this being accompanied by slowing of the rate of beat and irregularity. The effects in this curve resemble so closely those produced by vagus stimulation, that they might be explained entirely by ascribing them to the action of this nerve.

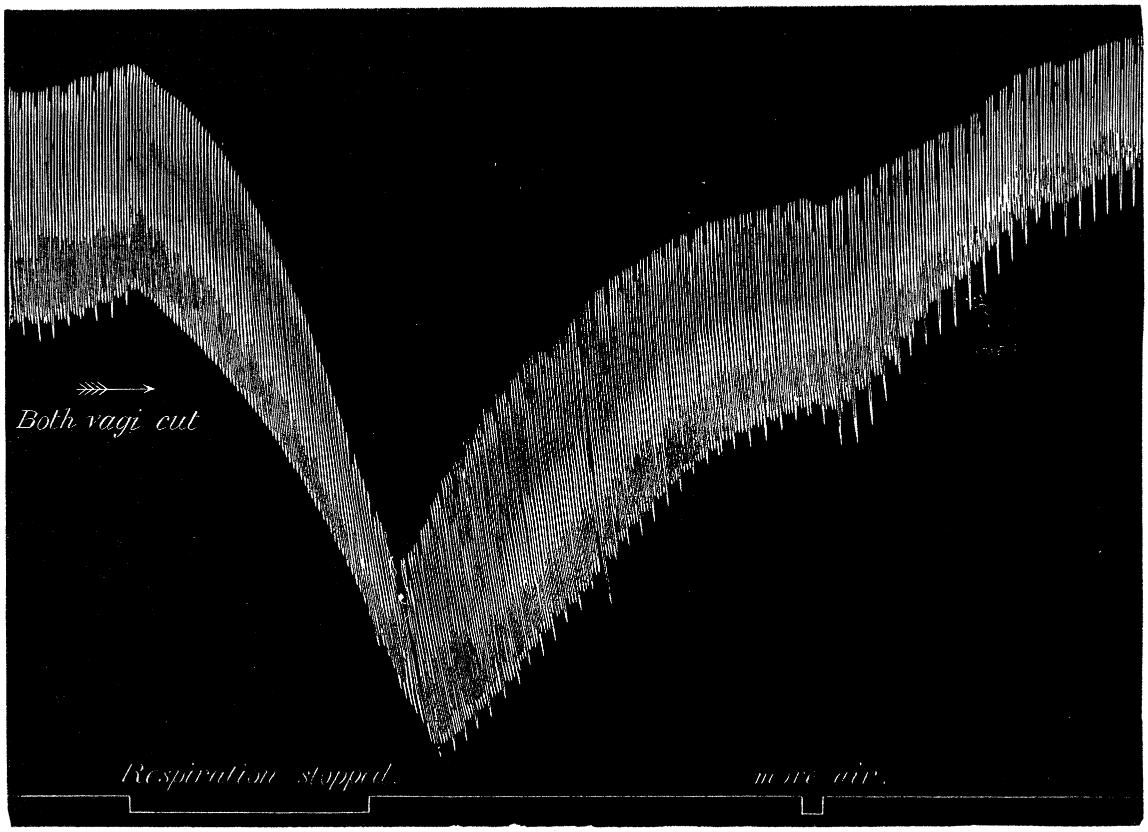
After section of both vago-sympathetics, myocardiographic records of temporary asphyxia show that as a result of stopping the respiration the contractions of the auricle become reduced in force, the shortening of the fibres of which its wall is composed being diminished, while at the same time the degree of expansion in diastole is also lessened. In the case of the ventricle, the effect of the interruption of the aëration is to cause progressive weakening, resulting in increased expansion in diastole and diminished contraction in systole. That this expansion is not due to increase in the height of the blood-pressure in the systemic arteries is shown by kymographic curves taken along with the myocardiographic tracings, which may indicate a fall of pressure in the systemic arteries during the period of interrupted respiration (when the dilation of the left ventricle is most marked). We may conclude, therefore, that the tonicity of the auricular wall in diastole is increased, although their force is weakened by asphyxia, while the ventricular muscle is weakened by the same cause, and that these effects are not due to the action of the vagus nerves, since they show themselves after these nerves have been cut.

It is important to note that the changes we have just referred to as taking place in the force of the ventricular and auricular contractions, after the vago-sympathetics have been cut, occur much more slowly after cessation of the respiration than do the

vagus effects, which show themselves usually in about a quarter of a minute after the respiratory arrest.

When the vagi are intact the interruption of the respiration usually leads to great irregularity of the heart, due in part to excitation of the vagus, seeing that it does not show itself if the nerves have been cut. That it is not due to the vagus action alone is sufficiently evident from the fact that it occurs less readily from simple direct or reflex excitation of the vagus by means of an electric stimulus. That it is in part due to increased excitability or increased excitation of the ventricles is of course probable.

Fig. 37.



Cardiometer curve [two-thirds original size], contraction causing upward movement of the lever point. This shows one of the effects of stopping the respiration after both vagi have been cut. The heart becomes greatly dilated with progressive increase in the residual blood due to progressive weakening of the heart walls. The improved condition of the heart, upon giving the animal more air to breathe, is well shown in the second part of the curve.

To summarise: *The first effect of asphyxia upon the heart is to produce vagus action due to excitation of the vagus centre in the medulla, as its appearance can be prevented by section of the vago-sympathetics. There is also gradually produced a progressive weakening of the auricular and ventricular contractions, due presumably to the imperfect supply of oxygenated blood to the heart muscle. The*

output of the heart would presumably be increased in non-curarised animals, owing to the high venous pressure, which would probably more than counterbalance the diminution of the output which vagus action alone would bring about. It need hardly be added, that owing to the contraction of the vessels in certain vascular areas the blood-pressure in the systemic arteries is raised. Considering these facts, it may be noted, in the first place, that the rise of arterial pressure is not, as in the ordinary physiological rise of pressure which is produced during muscular exertion, or as a result of stimulation of sensory nerves, accompanied by augmentor effects on the heart; that, on the contrary, the rise of pressure in asphyxia is associated with vagus action, so that we have the apparent anomaly of increased work thrown upon the heart, while, at the same time, its action is so limited by the vagus as to reduce its work and tissue waste as far as is compatible with continuance of the circulation. A sufficiently probable explanation of this is obvious. In asphyxia the system as a whole is in danger through arrest of the supply of oxygen. This danger may be diminished by a change in the distribution of the blood, so that these tissues which are of vital importance to the economy are supplied richly with blood, while those organs whose function can be temporarily interrupted without harm to the system, as, for example, the kidney, spleen, and digestive system are rendered anæmic, their vessels contracting strongly when the supply of oxygen in the blood is diminished. Now, the two organs of the body whose supply of oxygenated blood cannot be interrupted, even temporarily, without danger to the system are the central nervous system and the heart. The brain during asphyxia is enormously congested,* while, by the action of the vagus nerve, the tissue waste of the heart, and, therefore, the amount of oxygen which it requires, is reduced as low as is compatible with a continuance of the circulation. This explanation of the changes in the heart and circulation which take place during asphyxia is teleological, but seems to us so obvious in view of the facts before us, that we have not hesitated to state it.

It is possible that the indigestion and scanty urine in patients suffering from heart-failure may be, in part, due to the constriction of the walls of the blood-vessels of the kidneys and digestive tract—which, as we have seen, takes place so surely in asphyxia —although it is possible that these phenomena of heart-failure are due exclusively to the fall of arterial and rise of venous pressures.

CONCLUSION.

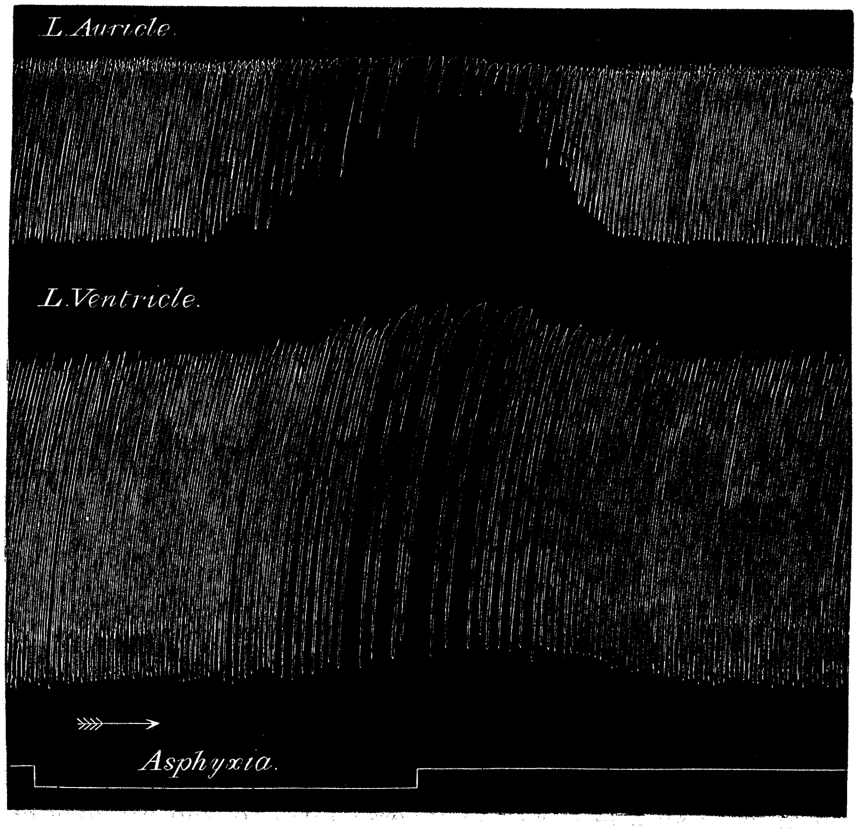
In the foregoing pages we have sought to state as clearly as lay in our power the principal results of the long series of observations which we have made on the nervous and other mechanisms of the Mammalian heart. Our communication is, to our regret, a very long one, and on that account we feel it our duty to give here some

* ROY and SHERRINGTON: "On the Regulation of the Blood-Supply of the Brain," 'Journal of Physiology,' vol. 9, 1890, p. 85.

such *résumé* of its contents as will enable those interested in the subject to obtain a knowledge of the scope of the paper without being obliged to wade through its many pages.

A short *résumé* has the disadvantage that its very brevity makes it difficult to understand and easy to misunderstand; it may, on the other hand, be of value in that it *may* enable some who have been confused by the details of the article itself to see clearly the drift of our results.

Fig. 38.



Myocardiographic tracings [original size] of Ventricle (above) and Auricle (below), showing effects of arrest of respiration. Contraction causes downward movement in both. [The effects resemble those of simple excitation of the vago-sympathetic trunk.]

Our communication begins by stating that we have sought to study the action of the Mammalian heart in conditions (unexcised and intact) as nearly approaching the normal as we were able to make compatible with the employment of exact methods of research. This is followed by a general consideration of the difficulties attendant upon such a study, and of the means by which these difficulties may be overcome. (Pp. 199–201.)

Under the heading of "Methods," we describe a *cardiometer* which we employed to measure the contraction volume and the "output," as well as the changes in the

volume of the heart other than those due to its rhythmic contractions and expansions. A description is also given of the method of employing it, together with a statement as to the degree of accuracy with which the instrument supplies information regarding changes in the volume of the heart. We then describe an automatic counter, which we employed for measuring out and recording the output of the organ, as obtained by the cardiometer. (Pp. 201–207.)

This is followed by a description of our *myocardiograph*, which we made use of to record the contractions and expansions of any part, or parts, of the ventricular and auricular walls without interfering with the movements of the heart. In most cases we employed this instrument to obtain simultaneous records of the contractions of one auricle and one ventricle. We state also our doubts as to the value of observations made on the heart by "*button*" cardiographs. (Pp. 207–209.)

Section III. begins by a consideration of the relationship between the circumferences of a hollow spherical muscle and its cubic contents, this being illustrated by a diagram, and one or two concrete examples with regard to the bearing of this subject upon the physiology of the ventricles.

We then state the relation between the circumference of a hollow spherical muscle and the resistance to contraction of its walls. Reference is also made to the elastic resistance which the heart wall itself offers to contraction, and the bearing of this upon the production of negative pressure within its cavity under certain conditions.

We then consider briefly the effect on the ventricular contraction of changes in the blood-pressure within the aorta and pulmonary arteries, pointing out how much the heart has in common with the voluntary muscles of the body, and explaining why the amount of residual blood is liable to changes, concluding with a few remarks upon "failure of the heart." (Pp. 209–215.)

In Section IV. we enter upon a study of the effects of the vagus nerve upon the heart. We begin with the changes in the contraction-volume, and point out that, at first sight, our curves seem to show that, other things being equal, the volume of blood expelled at each systole varies in inverse ratio to the rapidity of heart-beat. We show, however, that this general law does not hold good for vagus slowing (if, indeed, it be exact for slowing of any kind) which is found to be accompanied by a lowering of the output. That, with moderate slowing, this diminution of the output may be as much as 30 or 35 per cent., and still more with extreme slowing. (Pp. 215–217.)

We then speak of the increase in the amount of residual blood in the heart which is produced by vagus excitation, showing that this does not necessarily indicate any weakening of the ventricular contractions.

We next analyse myocardiographic records of the action of the vagus upon the heart, showing that the auricular contractions are weakened or arrested, and noting that the influence of the vagus upon the force of the auricular contractions bears no constant proportion to the vagus slowing. By strong vagus excitation or by muscarin the auricles may be completely arrested, it may be, for hours. This complete arrest

is, in some cases, led up to by progressive weakening, but sometimes arrest occurs immediately after fairly strong beats, or with fairly strong beats presenting themselves at times during the arrest. These latter cases may be explained by weakening of the excitations which reach the auricles from the sinus, although they are possibly due to diminished excitability of the auricles. (Pp. 217–222.)

On coming to the effect of the vagi upon the ventricles, we find that the distension of the heart during vagus action is due to the ventricles being more expanded both in diastole and in systole. We point out that the increased volume of the heart at the end of systole is a necessary result of the increased contraction volume, and combat the conclusions of those who ascribe it to weakening of the ventricular walls, pointing out that the greatly increased contraction volume increases to a corresponding extent the work done at each contraction. We give detailed reasons for concluding that this suffices to explain the apparent weakening of the ventricular contractions. (Pp. 222–224.)

We then examine the influence of the vagus upon the tonus of the relaxed ventricles, and point out that the great distension during vagus action is due entirely to increased intra-ventricular pressure during diastole, and not, as has been asserted by some, to any change in the elasticity of the relaxed ventricular wall. (Pp. 225–227.)

Next, we consider the cause of the rise of venous (systemic and pulmonary) pressure, and find that this is due not to any increase in the amount of blood entering the veins in a given time, or to contraction of their walls, but that it is to be ascribed to the diminished inflow into the ventricles.

The cause of this diminished inflow into the ventricles, leading to corresponding diminution of the output is twofold, namely weakening, or arrest of the auricles, and, secondly, the elastic resistance of the ventricular wall to distension. We show that this explanation must apply to both sides of the heart and that observed facts correspond with it.

We then consider the after-effects of vagus excitation, and show that the temporary increase in the output which is sometimes present may be explained by a temporary increase in the force of the auricular contractions, and by the venous pressure taking some little time to fall after the vagus excitation has ceased. (Pp. 227–231.)

After this we examine the influence of the vagus upon the heart rhythm, and show that when the vagus excitation reaches a certain degree (varying in different animals), the ventricles begin to beat independently of the sinus and auricles, the rhythm, which is at first slow and irregular, gradually becoming fairly rapid and almost completely regular.

This rhythm, we show, must be looked upon as the same as that which, as WOOLDRIDGE and TIGERSTEDT observed, makes its appearance when the ventricles are severed from the auricles. We point out, however, that the independent ventricular rhythm of vagus action is characterised by the slowness with which it establishes itself. (Pp. 231–233.)

This characteristic is due to the lowering of the excitability of the ventricles produced by vagus action, and we adduce a considerable number of facts showing that the vagus *does* lower the excitability of the ventricles, and that, by means of muscarin and by discontinuous stimulation of the vagus, it is possible to isolate the influence of the vagus on the rhythm and force of the auricles from its influence upon the excitability of the ventricles. The power of the vagus to stop the ventricles temporarily can only be explained by this diminution of their excitability.

We show that, with a certain degree of vagus excitation, irregularity of the ventricles necessarily results, in consequence of the sinus and the ideo-ventricular rhythms interfering with one another; that this is the common cause of irregularity, and that irregularity may also be caused by the auricles not responding to all the impulses which reach them from the sinus.

We explain that, in rare instances, direct excitation of the vagus may so lower the excitability of the ventricle that the contractions may not extend over the whole of their walls, and may in this way produce the apparent weakening which is sometimes met with. (Pp. 233–238.)

In Section V. we pass on to study the effect of direct excitation of the *nervi augmentores* (*accelerantes*) upon the heart, and show that the acceleration of the rhythm may be extremely slight if the heart be beating fast, and that the acceleration and augmentation of force of the heart bear no constant proportion the one to the other. The augmentor nerves increase the diastole expansion of the auricles and also increase their systolic contraction, but these two effects do not go hand in hand. (Pp. 238–242.)

Excitation of the augmentors increases the output of the heart, owing to the increased force and frequence of the auricular contractions, the result of this being that the pressures in the systemic and pulmonary arteries rise, while the systemic and pulmonary venous pressures fall. If there be but little quickening the contraction volume of the ventricles is increased.

The augmentors, on direct stimulation, cause a slight increase in the diastolic expansion of the ventricles, which is passive in nature and due to the increased force of the auricular contraction. The force of the ventricular contractions is increased; they contract more completely, diminishing the amount of residual blood in spite of the fact that the arterial pressure is usually somewhat raised. (Pp. 242–244.)

There are certain nerve fibres, other than the nervi augmentores proper, which pass from the stellate ganglion to the heart, sometimes by the annulus of VIEUSSENS to the inferior cervical ganglion, but sometimes as separate branches passing directly to the heart from the "ganglion stellatum" or the "annulus." On peripheral excitation of the cut nerves, there is marked weakening of the contractions both of the auricles and of the ventricles, usually with some degree of slowing, this being sometimes followed by a very well-marked increase in the force and frequence of

the auricular and ventricular contractions. They may be vaso-constrictors for the coronary vessels, although we give no proof of this. (Pp. 244–247.)

There are nerve fibres which descend to the heart by the vago-sympathetics which, on excitation, under certain conditions, increase the force and frequence of the auricles and ventricles, and which may be vaso-dilators for the coronary vessels. (Pp. 248–250.)

Reflex excitation of the vagus produces results which are the same as those of direct excitation of the nerve, and the curves are more typical and satisfactory than those obtained on direct excitation of the nerve. (Pp. 250–254.)

Excitation of a mixed nerve, like the sciatic, usually produces effects on the heart similar in kind to those due to direct excitation of the augmentors, but the phenomena are complicated by the greater rise of the pressure in the systemic arteries. Sometimes the increase in the force of the ventricle more than counterbalances this increased resistance to contraction, and the amount of residual blood in the left ventricle is reduced; in other cases, the increase in force of the ventricular contractions is not sufficient to counterbalance the increased resistance, and the residual blood in the left ventricle is increased. (Pp. 254–258.)

In Section IX. we show that excitation of the central end of a mixed nerve, like the sciatic or splanchnic, usually affects both the augmentor and vagus centres in the medulla and that, in nearly all cases, the augmentor centre is the more strongly excited of the two, so that augmentor effects show themselves during the excitation, but are succeeded by vagus action on ceasing to excite the nerve. In many cases augmentor effects alone show themselves. When excited reflexly the augmentor centre ceases to act earlier than the vagus—the opposite therefore to what takes place with direct excitation. In rare cases, the excitation of the vagus-centre may be stronger than that of the augmentor from the first. Although, in the absence of any augmentor action, the vagus does not reduce the force of the ventricular systole, it does unmistakably have the power of inhibiting the strengthening influence which the augmentors can exert upon the ventricular contractions. (Pp. 258–262.)

In Section X., upon the part played by the vagus in the economy, we show that vagus excitation relieves the heart of work, and, therefore, of waste to as great an extent as is compatible with a continuation of the circulation, and conclude that the vagus acts as a protective nerve to the heart, reducing the work thrown upon that organ when, from fatigue or other cause, such relief is required by it. The presence in the sciatic and other mixed nerves of fibres which cause reflex excitation of the vagus would seem to indicate that this nerve may be used by other parts of the body to diminish the output of the heart and lower the blood pressure, thereby reducing the activity of the circulation as a whole. The influence of the blood-pressure in the systemic arteries on the degree of vagus activity, and the readiness with which the vagus centre is called into play by raising the intracranial pressure, indicate that the vagus mechanism is specially employed in lowering the circulation so as to limit

cerebral congestion. The vagus acts chiefly in the interests of the heart and central nervous system.

The power of the vagus over the heart is limited, and the ideo-ventricular mechanism, which comes into play when the vagus action exceeds a certain limit, must be looked upon as the means by which arrest of the circulation and death are prevented, whenever from any cause the nerve exerts a maximum influence. The power of the vagus to lower the excitability of the ventricles makes their temporary arrest possible, but this reduction of excitability of the ventricles cannot be kept up, no matter how strong the stimuli applied to the nerve, for a period long enough to endanger the circulation. (Pp. 262–264.)

In Section XI. we show that the function of the augmentors in the economy is to increase the work and tissue waste of the heart as part of the mechanism by which the nervous system governs the circulation, and that the augmentor mechanism sacrifices the heart in order to increase the output of the organ, and enable the ventricles to pump out their contents against heightened arterial pressure. Such excessive action of the heart is limited by the vagus, which, as we have seen, readily steps in, so soon as the call for increased supply of blood has ceased. It may do so earlier, presumably because the increased blood-pressure or the fatigue of the heart call for vagus intervention. (Pp. 264–266.)

In Section XII. we consider the mode of interaction of the vagi and augmentors; we point out that when the vagi are paralysed by section or atropin, the augmentors have no control over the cardiac rhythm, and that, therefore, they can only act by inhibiting the influence of the vagi on the rhythmic centre of the heart. When neither nerve is acting on the auricles they contract with a certain force which is increased by the augmentors, and diminished or inhibited by the vagi. The force of the ventricular contractions is increased by augmentor action; this increase can be inhibited by vagus excitation, which latter has otherwise no power to reduce the strength of the ventricular contractions. (Pp. 266–269.)

The force of the heart's contractions is influenced by other factors than the vagi and augmentores, and other nerves. The pressure of the blood in the coronary arteries is one of the most important. If this be lowered, the contractions of both auricles and ventricles diminish in strength, while a rise of pressure in the systemic arteries causes an increase in the force of the heart's contractions, so that the force of the heart's contractions is, to a certain extent, regulated automatically by changes in the blood-pressure in the aorta. This is one of the variable quantities affecting the work of the left ventricle.

Change of the volume of the blood in the body affects greatly the contraction-volume and output of the heart. Injection into the veins of a volume of defibrinated blood equal to one-tenth of the total blood in the body may double the output. It is important to note here that there is no increase in the strength of the ventricular contractions; increase in the work, therefore, of the ventricles, due to increase in the

output has no tendency to automatically increase the force of the ventricular contractions. We refer to the bearing of this in cases of plethora. (Pp. 269–274.)

Increase of the watery constituents of the blood increases the contraction volume and output to the same extent (though only temporarily) as does transfusion of blood, but acts still more unfavourably on the heart, seeing that the work done by the ventricles is increased, while the nutritive value of the blood supplied to the coronaries is diminished.

The increased output of the heart both in plethora and in hydræmia is due to rise of pressure in the systemic veins, increasing the volume of blood which enters the right ventricle during diastole. We refer to the bearing of these facts upon the treatment of chlorosis and heart disease. (Pp. 274–278.)

In Section XIV. we consider the limits of the power of the heart to perform the work thrown upon it, and show that, in strictly physiological conditions, and in spite of the beautiful mechanism by which the force of the ventricular contraction is regulated, the heart, like the voluntary muscles of the body, is liable to fatigue when the work thrown upon it greatly exceeds that required to maintain the circulation under ordinary circumstances. We take as example the increase in work thrown upon the organ during active muscular exertion, and show that exertion and endurance of fatigue are limited mainly by the limited power of the heart to continue supplying the increased amount of blood which is required by the acting voluntary muscles. We show that those luxuries which are forbidden or limited in "training," and which are known to hinder prolonged exertion, such as water, alcohol, tobacco, caffein, all directly weaken the force of the heart's contractions, and in the case of water, place the organ under a disadvantage. Also that fatigue of the heart leads to dilation of the organ.

On comparing the power of fatigued ventricles to carry on increased work, as compared with well-nourished unfatigued ventricles, it is found that not only is the strengthening effect of the augmentor nerves upon the individual contractions less in the former case, but also that the fatigued, and, therefore, dilated heart is, *per se*, unfavourably placed for meeting increase in the work thrown upon it. An explanation is given of the reason why, in heart disease, failure takes place during exertion. (Pp. 278–282.)

The part played by the vagus in protecting the diseased heart from harmful overwork is referred to, and it is shown that the irregularities of the heart in disease may be explained by the mode in which this nerve, when acting powerfully, releases the ventricles from the control of the rhythmic centre in the sinus. The chief forms of rhythmic and arhythmic irregularity are considered, and it is shown that these correspond with the forms of irregularity which can be produced by vagus action. The irregular heart expends more energy, and its tissues, therefore, are more wasted for a given amount of work, than the heart which is beating regularly. (Pp. 282–284.)

The effect upon the heart of imperfect aëration of the blood is, first of all, to produce

powerful vagus action from the medullary centre; this is, usually, though not always, accompanied, in curarised animals, by diminution of the output of the heart. But reasons are given for assuming that the output would be increased in uncurarised animals, owing to the high venous pressure which results from struggling. Besides the vagus action it can be shown that temporary asphyxia causes progressive weakening both of the auricles and of the ventricles, and attention is drawn to the fact that the considerable rise of pressure in the systemic arteries in asphyxia is accompanied by vagus effects upon the heart, and not by augmentor action, as is the case, so far as we know, in all instances in which the vaso-constrictor centre is excited in the normal individual.

It is noted that the changes in the heart and circulation which take place during asphyxia point to the conclusion that, when the total amount of oxygen in the blood is lowered, it is for the benefit of the economy that those organs, such as the central nervous system, whose continuous blood supply is a vital necessity, should be richly supplied with blood by constriction of the vessels of the spleen, kidney, and digestive system, whose blood supply can be cut off temporarily without danger to life, and also that the heart should carry on the circulation in a manner involving as little waste as possible of its own substance. This, as we have seen, it is the function of the vagus nerve to bring about. (Pp. 284–288.)